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HANDBOOK FOR FORECASTERS IN THE BAY OF BENGAL

by

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SEPT 1973

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A literature search was conducted with the objective of assimilating information from widely diverse sources to provide the operational Navy forecaster with a single reference text for the Bay of Bengal. To avoid presenting conflicting points of view about the various phenomena discussed, the author has given the viewpoint which, at this time, seems most reasonable.

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FOREWORD

The developing United States presence in the Indian Ocean has created a need for meteorological information and forecasting aids in an area hitherto little traveled by U.S. Forces. This document fills a gap in the technical libraries of U.S. Navy forecasters concerned with operational forecasting in the Bay of Bengal.

This study by INSTR LCDR M. J. CUMING, of the British Royal Navy, was completed during his tour of duty as an exchange officer at ENVPREDRSCHFAC. Similar handbooks are planned for other areas where a void exists in the catalog of aids available to operational forecasters.

Comments concerning the usefulness, completeness, and appropriateness of this document, including suggestions for additional information or study, will be gratefully received.

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ABSTRACT

A literature search was conducted with the objective of assimilating information from widely diverse sources to provide the operational Navy forecaster with a single reference text for the Bay of Bengal. To avoid presenting conflicting points of view about the various phenomena discussed, the author has given the viewpoint which, at this time, seems most reasonable.

The approach adopted has been to describe and discuss the various large-scale and synoptic scale features and then to link all the components together in a description of the "March of the Seasons." Mean climatic charts are presented and, wherever possible, typical satellite photographs are presented to illustrate various features.

I. GENERAL INTRODUCTION

The Bay of Bengal is an area of increasing operational significance to the U. S. Navy and, hence, to the Navy forecaster. However, meteorological information concerning the bay is generally available only from widely scattered documents, many of which are not readily available to the operational forecaster. Even if these references were made available, a great amount of study time is needed to gain a working knowledge and understanding of the meteorological regimes and phenomena affecting the bay. In addition, much of the literature presupposes a considerable background knowledge of tropical and monsoon meteorology. Most U. S. Navy forecasters, however, have had experience only with mid-latitude meteorology, augmented perhaps by experience in the North Pacific Ocean.

This Handbook has been written with the objective of providing the busy operational forecaster with a single reference text for the Bay of Bengal. Such an objective requires that background information on tropical and monsoon meteorology be presented as well as a detailed description of the weather in the bay.

These requirements have largely dictated the size, scope, and layout of this Handbook. This is indicated in the list of contents. Basically, the approach adopted has been to describe and discuss the various large-scale and synoptic-scale features, and then to link all the components together in a description of the "March of the Seasons." The necessary climatological data is presented in appendixes A and B, while appendix C contains typical satellite photographs for the various seasons. Extensive cross-referencing has been used.

An important omission is a discussion of refractive index problems which are becoming increasingly important. Results of studies in this area will be published at a later date.

Throughout, the needs of the operational forecaster have been kept in mind; the Handbook is not intended for the research meteorologist. Since there are divergent opinions in academic circles concerning certain of the phenomena discussed, some selectivity has been necessary. Rather than present conflicting points of view which would lead to confusion rather than clarification, that viewpoint has been given which, at this time, seems most reasonable to the author.

Comments from operational forecasters on the usefulness of this Handbook are invited. Also, details of "in situ" case studies and experiences would be most welcome.

2. PHYSICAL FEATURES

2.1 INTRODUCTION

The Bay of Bengal is open to the Indian Ocean to the south only; in other directions the bay is surrounded by land, much of it extremely mountainous. The land masses around the bay have a profound effect on the weather regimes of the area and a knowledge of the relevant physical features of these land masses is essential to an understanding of the meteorological phenomena affecting the Bay of Bengal.

2.2 LOCATION

The peninsula forming the sub-continent of India (see Figure 2-1) has its north base resting on the Himalayan Massif and extends southward into the Indian Ocean. The island of Ceylon lies off the southeastern tip of India, the combined land mass extending southwards to about 6 degrees north of the equator. The wedge-shaped Indian Peninsula divides the northern part of the Indian Ocean into two main seas; to the west of the Peninsula lies the Arabian Sea, while to the east lies the Bay of Bengal.

In the north, the head of the Bay of Bengal is formed by the low-lying, densely populated area known as the Mouths of the Ganges. In the northeast the bay is bounded by Burma, and in the east by a line connecting the southwest tip of Burma (Cape Negrais), the Andaman and Nicobar Islands, and northwest Sumatra (Kutaradja). This line separates the Bay of Bengal (to the west) from the Andaman Sea (to the east). However, in this Handbook, the term Bay of Bengal will be used to include both the bay proper and the Andaman Sea.

2.3 OROGRAPHY

Figure 2-1 shows a simplified picture of the elevation of the relevant land masses surrounding the Bay of Bengal.

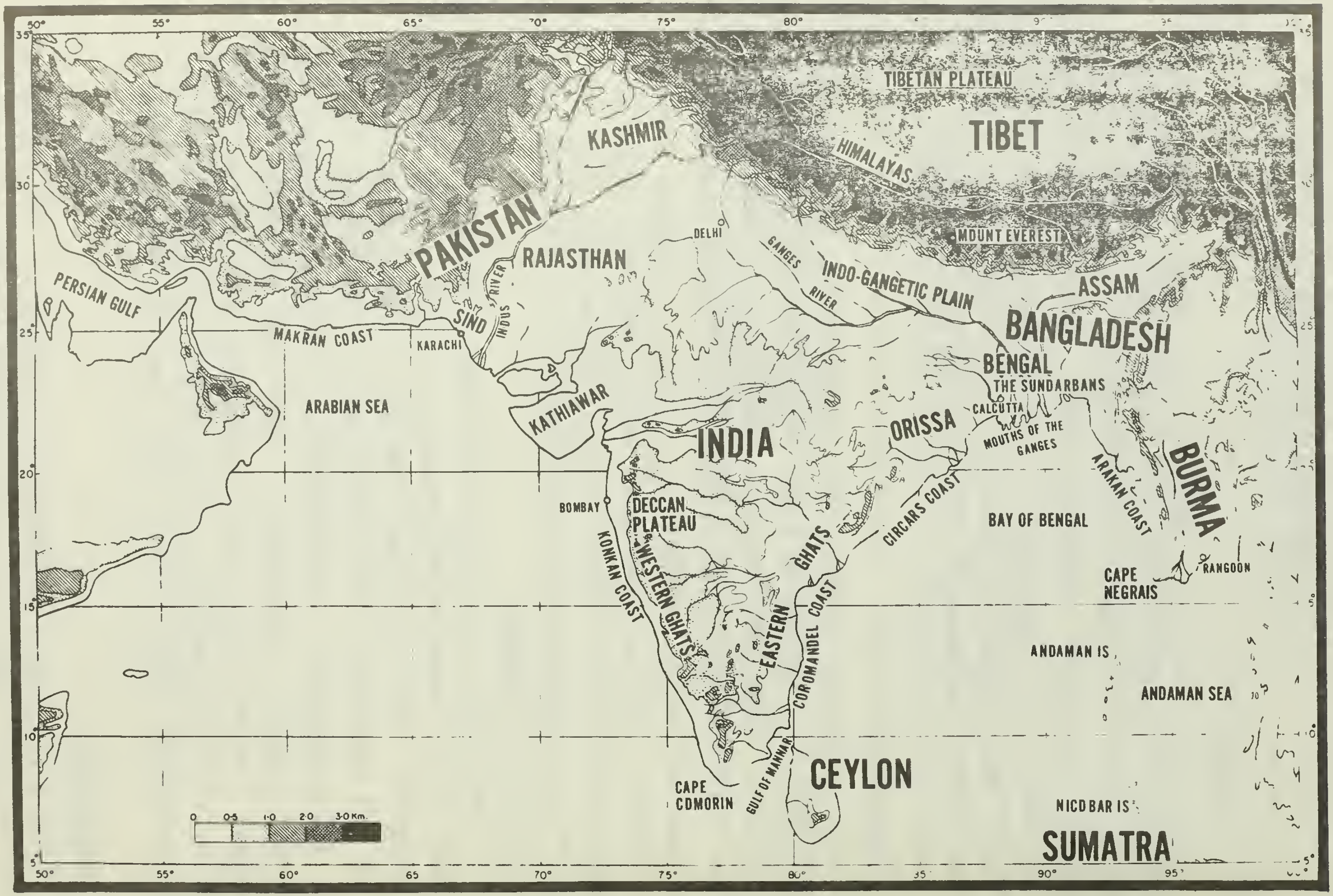


Figure 2-1. Locator map of Indian subcontinent

A more detailed map should be studied to gain a better appreciation of the orographic features.

South of about 20N the Indian Peninsula is surrounded by a relatively narrow coastal strip. Further inland the ground rises fairly sharply to the Deccan Plateau which has a mean height of less than 3,000 ft. Worthy of mention are the mountain chains known as the Western and Eastern Ghats.

The Western Ghats, shown in Figure 2-1, lie along the western coast of India south of about 20N. They are most prominent in the south, reaching a maximum height of about 8,000 ft. This coast has the wettest climate of the whole peninsula, the rainfall being particularly heavy on the slopes of the Western Ghats during the southwest monsoon of summer. The Eastern Ghats lie along the eastern coast of India south of about 20N. They are not nearly as well defined as the Western Ghats and are also situated further from the coast, the mean width of the eastern coastal plain being about 80 miles. The Eastern Ghats comprise groups of hills which rise to 2,000 to 4,500 ft and are intersected by various rivers flowing into the Bay of Bengal.

To the north of the Deccan Plateau, the Indo-Gangetic Plain continues to the foothills of the Himalayan Massif. To the west lies the low-lying area associated with the Indus River flowing into the Arabian Sea. To the east lies the vast drainage area associated with the Ganges, the Mouths of the Ganges forming the head of the Bay of Bengal.

Further north, the low-lying areas give way abruptly to the Himalayan Massif including the Tibetan Plateau. This area has a mean height of about 14,000 ft and there are extensive areas lying above 18,000 ft. The maximum height is, of course, the peak of Mount Everest -- 29,028 ft. This vast massif intrudes into the mid-troposphere (e.g., 500 mb)

and has a very significant effect on the hemispheric circulations at all levels, including the weather regimes of the Bay of Bengal.

The northeastern and eastern shores of the bay are shielded partially by extensions of the Himalayan Massif. One such extension runs almost due south down the western coast of Burma, the tops of some of the submerged peaks forming the Andaman and Nicobar Islands. These islands have no significant height, meteorologically speaking, but the Himalayan extension eventually rises from the ocean to form Sumatra and the off-shore islands. Sumatra has a backbone of mountains reaching heights of about 10,000 ft. The mountains along the west coast of Burma are backed by other higher ranges within the Indo-China Peninsula.

3. THE MONSOON REGIME

3.1 INTRODUCTION

The most significant meteorological phenomenon affecting the Bay of Bengal is, of course, the monsoon. Paraphrasing the Glossary of Meteorology (Huschke, 1959), this is a name for seasonal winds (derived from Arabic mausim, a season) and was first applied to the Arabian Sea, where winds blow for six months from northeast and for six months from southwest. The use of the name has since been extended to similar winds in other parts of the world. The primary cause of monsoon winds is the much greater annual variation of temperature over large land areas compared with neighboring ocean surfaces, thus causing an excess of pressure over the continents in winter and a deficit in summer. However, other factors, such as the land relief features, have a considerable effect.

Although a monsoon system requires a seasonal change in wind direction, in India the term "monsoon" is applied chiefly to the southwest monsoon of summer and, by extension, to the rains which it brings. Thus, in Indian writings, the arrival of the southwest monsoon is often used to denote the onset of the summer rains. However, in this Handbook the term "monsoon" is to be regarded as a seasonal wind only.

3.2 DEFINITION

The word "monsoon" implies seasonality--surface winds which flow persistently from one general direction in summer and just as persistently from a markedly different direction in winter. To classify objectively an area as monsoonal, one must lay down criteria concerning the seasonal changes of direction, and persistence. In addition, those areas should be excluded in which the seasonal wind shift only reflects

a movement in the mean tracks of moving systems. Many meteorologists have attempted to lay down a satisfactory definition of the monsoon area; the latest (and best) is attributed to Ramage (1971). He defines the monsoon area as encompassing regions with January and July surface circulations in which:

(a) the prevailing wind direction shifts by at least 120° between January and July,

(b) the average frequency of prevailing wind directions in January and July exceeds 40%,

(c) the mean resultant winds in at least one of these months exceeds 3 meters/sec, and

(d) fewer than one cyclone-anticyclone alternation occurs every two years in either month in a 5° latitude-longitude rectangle.

Following these criteria and "squaring off," the monsoonal area is enclosed between 35N and 25S, and between 30W and 170E. This area is shown on Figure 3-1.

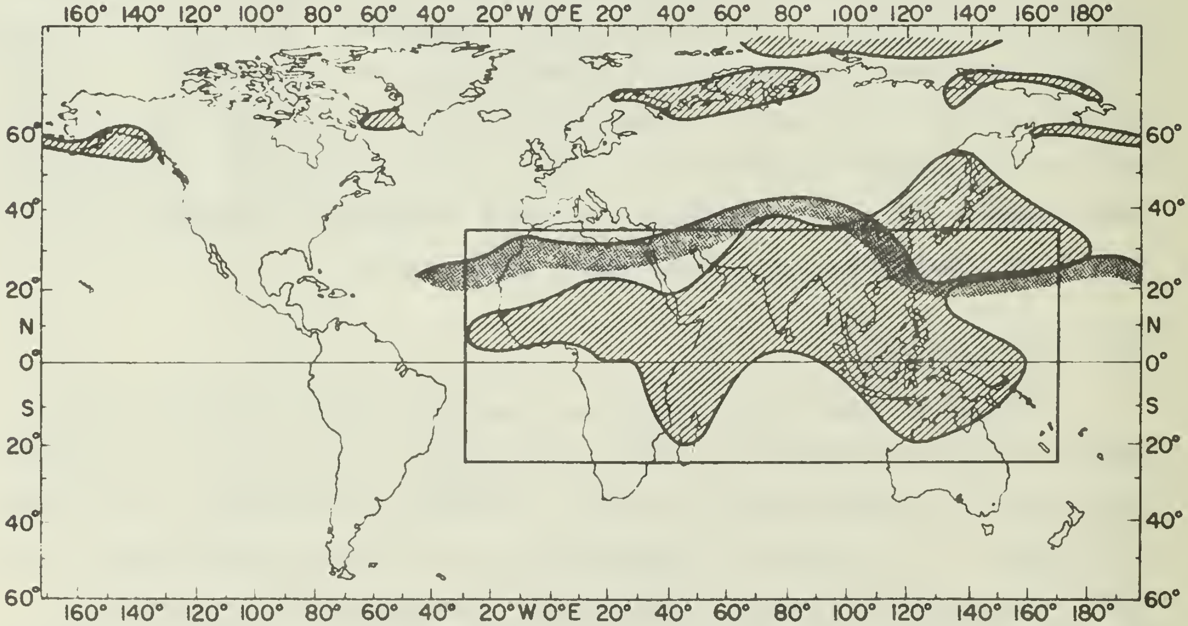


Figure 3-1. Final delineation of the monsoon region. Hatched areas are "monsoonal". Heavy line marks northern limit of the region within the Northern Hemisphere with low frequencies of surface cyclone-anticyclone alternations in summer and winter. Rectangle encloses the monsoon region (from Ramage, 1971).

It should be noted that this definition defines the monsoon as a surface wind. There are no weather considerations and, for example, the Sahara Desert is considered a monsoonal area..

3.3 THE MONSOON REGIME IN THE BAY OF BENGAL AND THE ROLE OF THE HIMALAYAN MASSIF

Monsoons are fundamentally due to the temperature gradients established between land and sea at different times of the year.

Confining the discussion to the Bay of Bengal and the relevant land masses, in January (winter) the surface air over the Indian Peninsula, particularly in the north, is generally colder than the air over the surrounding seas. Thus a low-level pressure gradient is established causing surface air to move from land to sea; this is the northeast monsoon. A compensating return circulation exists at higher levels. The Himalayan Massif prevents the southerly movement of extremely cold air which accumulates over central Asia, and the temperature gradient causing the monsoon flow is the comparatively weak one established between land to the south of the massif and the Indian Ocean. The northeast monsoon is therefore also comparatively weak, showing none of the violent "cold surges" which occur over the South China Sea and other areas caused by invasions of cold air emanating from the Siberian anticyclone (NWRF, 1969). Nevertheless, occasional outbreaks of cold air do reach the Bay of Bengal from a different source, causing temporary intensification of the northeast monsoon. These outbreaks are discussed in paragraph 4.7 under Western Disturbances.

In July (summer) the reverse process occurs. An intense heat low develops over India, the main heat trough lying far to the north more-or-less along the foothills of the Himalayas.

Air over the surrounding seas is now cooler than that over the land and the concomitant pressure gradient results in the southwest monsoon, a reverse circulation being established at higher levels. Again, the massif prevents any cold air originating in more northerly latitudes from penetrating southward and reducing the intensity of the trough. Thus, by preventing an influx of cold air from the north, the Himalayan Massif permits the heat trough to become more intense, and the southwest monsoon of summer is increased in intensity.

Apart from its effect on the monsoon winds over the Bay of Bengal and other areas, the Himalayan Massif has an important part to play in modifying large-scale atmospheric processes. The elevated surface of the massif absorbs incident solar radiation throughout the year (even in winter the Tibetan plateau is comparatively free of snow). This heated surface then supplies heat by way of long-wave radiation to the atmosphere in the vicinity of the plateau and, since the Himalayan Massif extends into and beyond the mid-troposphere, it acts as a heat source for those levels. This heat source plays a significant role in determining hemispheric circulation patterns throughout the year.

3.4 THE MONSOON LOW

According to the Glossary of Meteorology (Huschke, 1959), a monsoon low is "a seasonal low found over a continent in the summer and over the adjacent sea in the winter." It quotes as an example the low found over India in summer and the Bay of Bengal in winter. See Appendix B, Figures B1(a) through B1(d).

In the context used by the Glossary of Meteorology, a monsoon low may be regarded as the seasonal distribution of pressure causing the northeast monsoon of winter and the

southwest monsoon of summer. This pressure distribution is caused, in turn, by temperature variations as described in paragraphs 3.1 and 3.3. However some writers use the term "monsoon low" solely to describe the summer heat low over northern India and similar areas. The term "monsoon low" will not be used in this Handbook to avoid confusion with the "monsoon depression" (see paragraph 4.3). The term "monsoon trough" will be used for the axis of the area of low pressure caused by surface heating (see paragraph 4.2.5); closed isobars may or may not be found within this low pressure area.

3.5 THE SEASONS IN THE BAY OF BENGAL

There are basically four seasons which affect the Bay of Bengal. There is no universally recognized name for each of these seasons. Forecasters more familiar with weather conditions in more temperate latitudes often refer to them as winter, spring, summer and fall. It must be realized however, that these terms applied to the tropics do not have the same connotations as when applied to mid-latitudes, and that use of such terms implies only a time of year. Seasons and seasonal changes in the Bay of Bengal are associated with the wind regimes present. The following list shows the four basic seasons (defined by the approximate months associated with each) and the names commonly given them:

<u>December through March</u> (4 months)[1]
The Northeast Monsoon of Winter
The Winter Monsoon
The Cool Season

<u>April through May</u> (2 months)[1]
The Spring Transition Season
The Hot Season

---

[1]In some references, March is included in the spring transition season. This emphasizes the fact that the seasons are not fixed in time and vary considerably from year to year.

June through September (4 months)

The Southwest Monsoon of Summer

The Summer Monsoon

The Rainy Season

The Monsoon

October through November (2 months)

The Fall Transition Season

The Post-Monsoon Transition Season

4. METEOROLOGICAL PHENOMENA AFFECTING THE BAY OF BENGAL

4.1 INTRODUCTION

This section contains a description and discussion of the various meteorological phenomena which will be encountered by the operational meteorologist in the Bay of Bengal.

Paragraph 4.2 opens with a Discussion of Terminology wherein a list is given of some of the confusing (and confused) terms applied to the tropics. The terms to be used in this Handbook are then described.

There are three types of cyclonic vortex encountered in the bay. These are the Monsoon Depression (paragraph 4.3), the Mid-Tropospheric Cyclone (paragraph 4.4) and the Tropical Cyclone (paragraph 4.5). The last of these three, the Tropical Cyclone, is the most dangerous weather phenomenon occurring in the bay, although violent squalls are common at certain times of the year which can also cause severe damage to an unprepared ship. Such squalls are discussed in paragraph 4 6 together with other related phenomena.

Figure 4-1, extracted from Ramage (1971), illustrates schematically the circulation components of the monsoons, showing weather, levels of convergence and divergence, and vertical motion. This diagram will be referred to in the text.

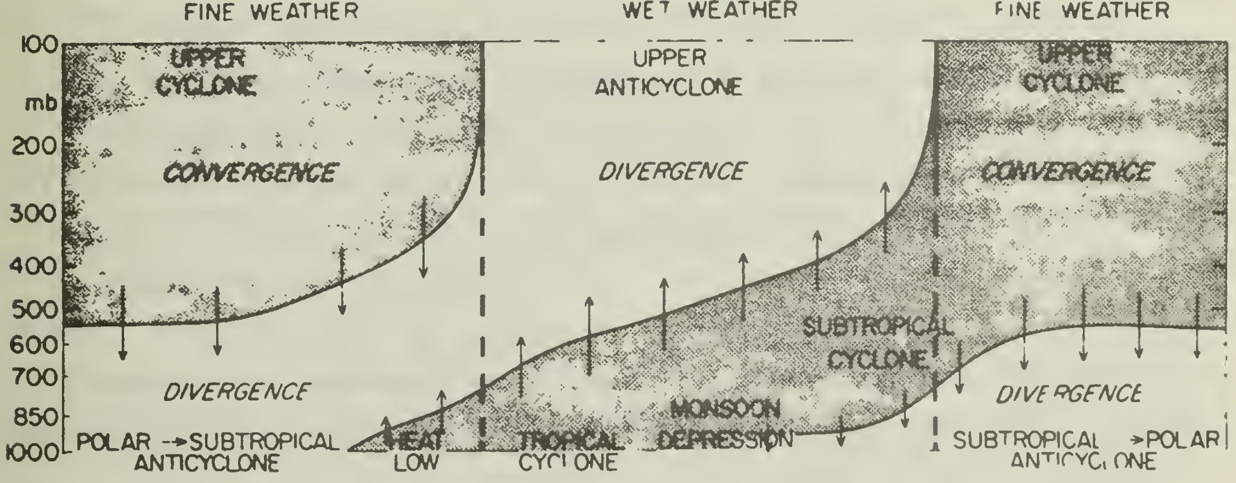


Figure 4-1. Circulation components of the monsoons arranged schematically according to weather, divergence, and vertical motion. Levels of nondivergence are denoted by heavy lines (after Ramage [1971]).

4.2 THERMAL FEATURES

4.2.1 Discussion of Terminology. Over the years, meteorologists have invented many terms to describe certain thermally induced features of meteorological systems found in the tropics. Such terms include:

intertropical convergence zone (ITCZ)
tropical convergence zone (TCZ)
tropical confluence
equatorial convergence zone
near-equatorial convergence zone
inter-tropical front
equatorial front
equatorial trough
near-equatorial trough
meteorological equator
doldrums
monsoon trough
cyclonic directional shear zone
cyclonic shear zone.

To bring order to this list of terms has proved impossible, for to do so requires definitions and descriptions allowing each term to be distinguished from all others, such definitions do not exist. Although, no doubt, the originator of each term had a clear idea of the distinction between his new expression and all others, careless usage has long since removed many of these subtleties. Also, some of the terms which contain outmoded concepts continue to be used (e.g., ITCZ).

Briefly, at one time "intertropical front" seemed a reasonable name for the line marking the meeting place or zone of air masses from the winter and summer hemispheres Careful and imaginative analysis of sparse data allowed this line to be positioned along the axis of the "(near-) equatorial trough of low pressure." On realizing the problems of imposing mid-latitude frontal concepts on the tropics, "intertropical front" was replaced by "intertropical convergence zone." The ITCZ was supposed to mark the zone of bad weather,

lying along the axis of the near-equatorial trough, caused by air converging from the two hemispheres. With the advent of satellites, it was soon realized that the ITCZ (based on cloudiness) did not necessarily lie along the axis of lowest pressure. Thus the ITCZ could no longer be called "inter-tropical" since it did not mark the meeting place of the air from the two tropics. Further study revealed that there was often more than one convergence line and, indeed, often more than one trough of low pressure. The existence was confirmed of troughs and convergence zones existing simultaneously in the winter and summer hemispheres.

Basically, the confusion of terms and ideas had been caused by forcing tropical phenomena to conform to overly-simple models extending mid-latitude concepts into the tropics.

The following terms will be used in this Handbook and are discussed in this section:

heat lows and heat troughs
near-equatorial troughs
near-equatorial convergence
monsoon troughs.

4.2.2 The Heat Low (or Thermal Low). The description given here also encompasses the heat trough (or thermal trough).

According to the Glossary of Meteorology (Huschke, 1959), a heat low or thermal low is defined as follows:

> *"An area of low atmospheric pressure (a low) due to high temperatures caused by intensive heating at the earth's surface. Thermal lows are common to the continental subtropics in summer; they remain stationary over the area that produces them; their cyclonic circulation is generally weak and diffuse; they are non-frontal."*

> *According to H. C. Willet (Descriptive Meteorology, 1944, p. 151): "The immediate effect of the local heating is to lift the isobaric surfaces in the atmosphere over the heat source. This produces an upper level high and an outflow of air aloft, which in turn reduces the surface pressure and consequently induces an inflow of air into the surface low."*

To amplify this brief description, the intensive heating of the earth's surface by the sun increases long-wave reradiation from the ground. This is absorbed by the lower layers of the troposphere and the consequent reduction of density is seen as a reduction of surface pressure. Since a well developed heat low is basically due to persistent solar heating, it follows that the area encompassed by the heat low must be more-or-less cloudless. If this were not so, the clouds would cut off the solar radiation reaching the ground and the heat low would decrease in intensity, eventually becoming undetectable. The air converging into the heat low fails to produce clouds in significant amounts for two possible reasons:

(a) lack of moisture in the converging air, and/or

(b) subsidence at higher levels.

Heat lows would therefore be expected to be found in desert regions and/or in latitudes occupied by the oceanic highs which cause persistent subsidence in the mid-troposphere, thus limiting the heat-induced convergence to a shallow layer (see Figure 4-1).

4.2.3 The Near-Equatorial Trough. The term "near equatorial trough" is used in this Handbook for any large-scale trough of low pressure lying between the sub-tropical high pressure belts of the northern and southern hemispheres. Such troughs are oriented approximately east-west and may or may not be associated with synoptic-scale disturbances. Such a trough may be found as far as 25° or more from the equator (e.g., over northern India in the summer). However, under these circumstances, it is better referred to as the "monsoon trough" (see paragraph 4.2.5). The principal near-equatorial trough is found in the summer hemisphere.

The weather associated with a near-equatorial trough is showery (compare with the minimum cloudiness associated with

heat lows described in paragraph 4.2.2) although, in general, the worst weather and maximum cloudiness occurs along the near-equatorial convergence zone (see paragraph 4.2.4).

Tropical analysts are familiar with the discontinuous movement of the near-equatorial trough; within a few hours its position may jump by many miles. Ramage (1971) has indicated a mechanism which explains this erratic movement by suggesting that, even in the winter hemisphere, the troughs are at least partially under thermal control. Surface air rises in the trough causing clouds, rain, and occasionally vigorous cyclonic circulations. The clouds cut off heating from the sun which is needed to maintain the trough. On the edge of the cloudy zone, sinking motion clears the skies and allows surface heating, thus leading to the development of a new trough and repositioning of the cloudy zones. According to Ramage, "This sequence could account for reports that the trough often appears to move discontinuously." In addition to this discontinuous movement, the existence of the trough is not necessarily continuous in time. In other words, the analyst may not be able to detect the trough at all times as its mean position moves north or south over the bay.

Figure 4-2 shows the annual latitudinal variation of the near-equatorial trough over the Indian Ocean.

4.2.4 <u>Near-Equatorial Convergence Zone</u>. This term will be applied to the zones of maximum cloudiness and precipitation found near, but normally not coincident with, a near-equatorial trough. These convergence zones also move discontinuously, such movement probably being due to the same mechanism as that causing the erratic movement of near-equatorial troughs.

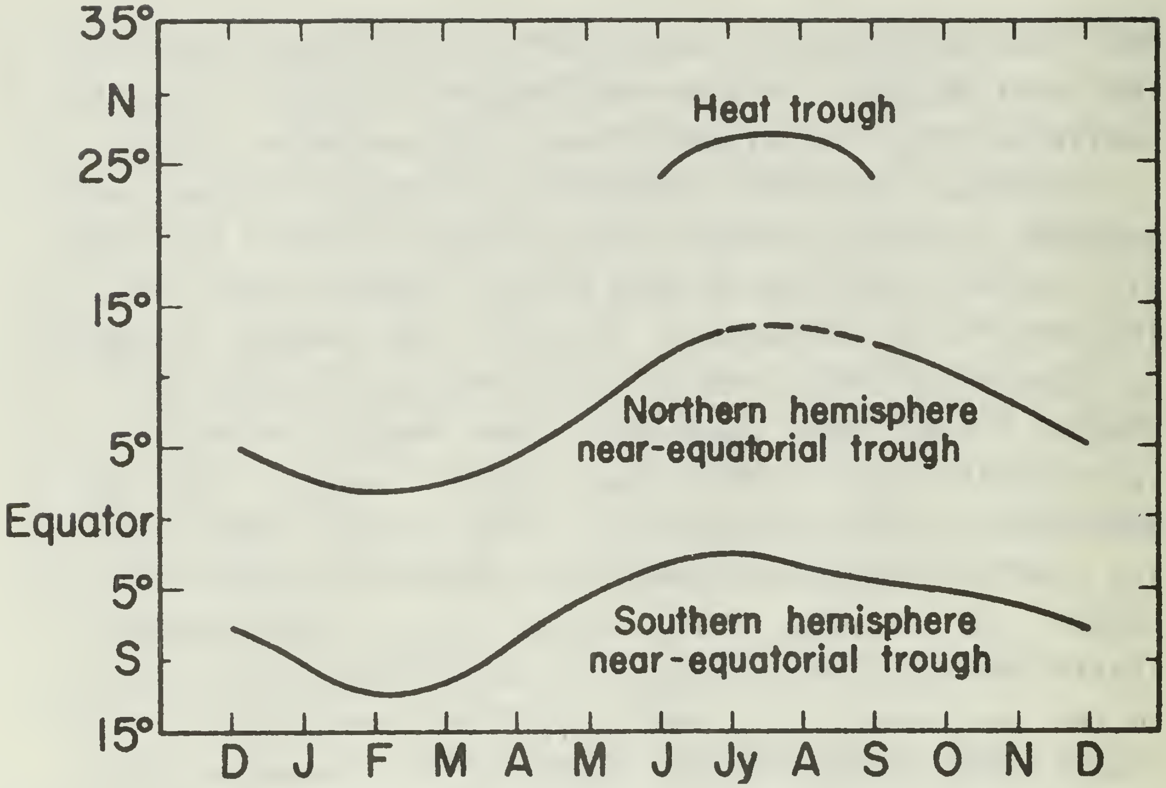


Figure 4-2. Annual latitudinal variation of lower tropospheric (1.5 km) pressure troughs over the Indian Ocean (after Ramage, 1971).

The near-equatorial convergence zone contains deep, intense cumulus convection. The convectively active part of the zone is usually fairly narrow (about 50 miles) and its latitudinal position varies in accordance with the near-equatorial trough. However, it is seldom found within 3° or so of the geographical equator. See Appendix C, Figure C-1.

4.2.5 <u>Monsoon Troughs</u>. It is difficult to define a monsoon trough with sufficient precision to allow it to be distinguished at all times from a near-equatorial trough. However, the term "monsoon trough" will be reserved for the intense trough of low pressure which occurs when the primary near-equatorial trough is displaced far to the north (e.g., over northern India and the northern part of the Bay of Bengal) and the southwest monsoon becomes well-established over the whole of the bay. See also paragraph 3.4.

4.3 THE MONSOON DEPRESSION

4.3.1 Introduction. During the southwest monsoon of summer, the monsoon trough is located far to the north (see Figures 4-2 and 4-3). The development of monsoon depressions is associated with the monsoon trough and they are thus confined to the head of the Bay of Bengal during the summer season. They are of particular interest to Indian meteorologists since they account for most of the southwest monsoon rainfall in northeast India. The development of a monsoon depression is not an isolated event within the monsoon circulation, but is associated with large-scale atmosphere circulation features (Gidley, 1972).

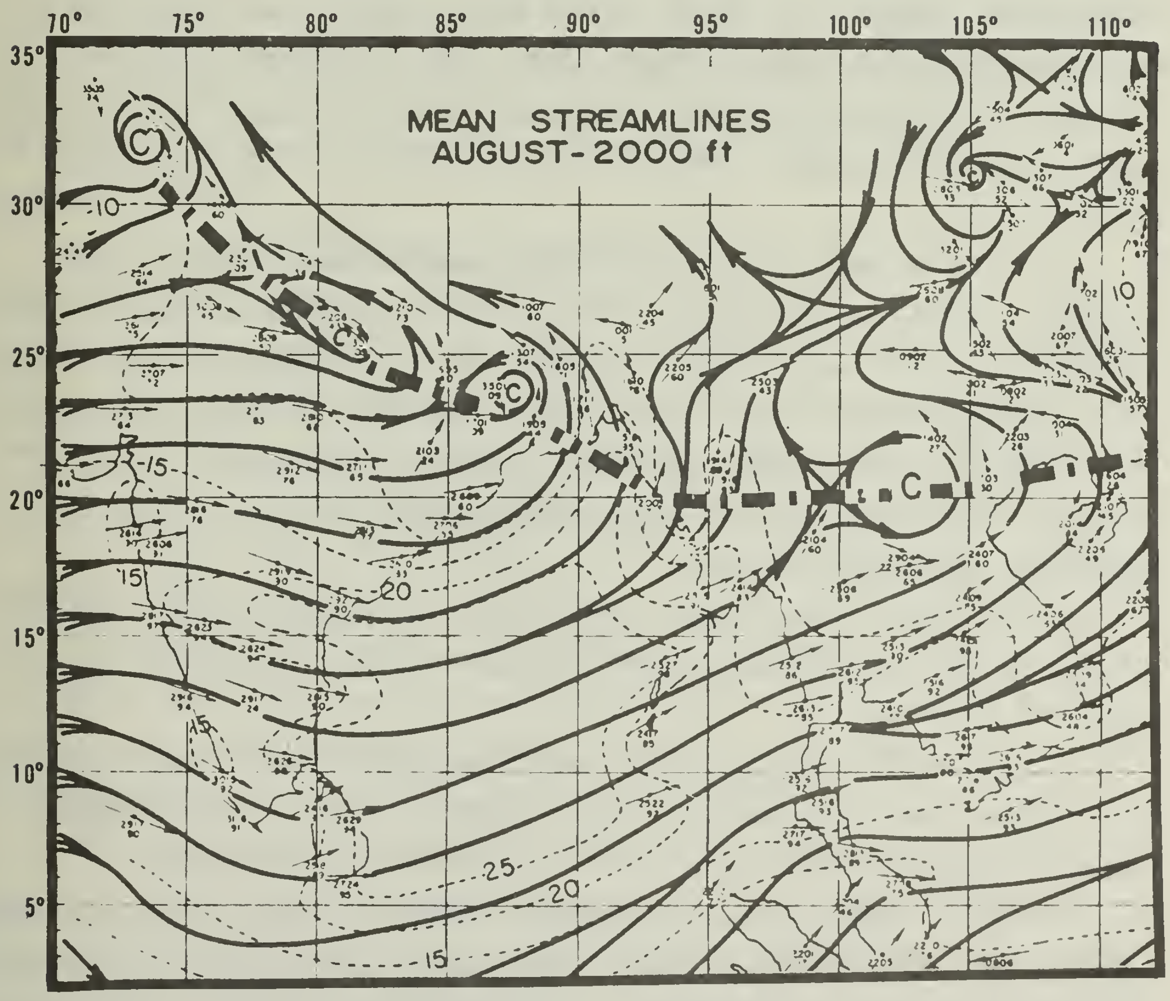


Figure 4-3. Mean streamline chart for August (2000 ft)

4.3.2 Description and Associated Weather. Monsoon depressions have different characteristics than the warm-cored tropical cyclones which develop over the Bay of Bengal during the transition seasons (see paragraph 4.5). Comparing warm-cored tropical cyclones (analagous to typhoons and hurricanes) with monsoon depressions, the latter have weaker surface pressure gradients, are less energetic, and do not depend significantly on the addition of sensible heat to inflowing surface air to maintain the circulation. According to Ramage (1971) there is evidence that monsoon depressions are most intense a kilometer or two above the surface and resemble both hurricanes (warm-cored) and mid-tropospheric cyclones (cold-cored)(see also paragraph 4.4). Central pressures range from 2 mb to 10 mb below normal and the circulation sometimes covers more than 250,000 sq km. (Figure 4-1 indicates the vertical distribution of convergence and divergence within the circulation of a monsoon depression).

Within a monsoon depression, winds over the Bay of Bengal seldom exceed gale force and the comparatively weak nature of the circulation is made more evident by the fact that the gradient level wind over the bay averages 20 to 25 kt during the summer monsoon period (Atkinson, 1971). Monsoon depressions do not develop into intense tropical cyclones for two reasons:

(a) Their position at the head of the Bay of Bengal prevents the sea from supplying sufficient sensible heat, and

(b) the vertical wind shear between the lower level westerlies and the higher level easterlies is too great. (See paragraph 4.5 for a more detailed discussion).

At one time, it was claimed that air-mass discontinuities were detectable within the circulation and that the observed rainfall could be explained by frontal concepts. This method of analysis has now fallen into disfavor.

Characteristically, the precipitation is mostly in the southwest quadrant of a monsoon depression (see Appendix C, Figure C-4). The air masses entering the circulation are predominantly tropical maritime, potentially unstable with high moisture content and, in their regions of heaviest precipitation, typically disgorge rainfalls of 4 to 6 in/day. On occasion, heavy thunderstorms are observed on the north side, which are not necessarily connected with the organized precipitation regions characterizing the southwest sector, but are more like the squall-line thunderstorms observed in warm sectors of mid-latitude cyclones. (Palmen and Newton, 1969). This can be seen in Appendix C, Figures C-4 and C-5.

According to Ramage (1971), "Pisharoty and Asnani found that heavy rains (often exceeding 10 cm in 24 hr) fall over a 400-km-wide strip to the left of monsoon depression tracks. The strip stretches from about 500 km ahead to about 500 km behind the center. Heavy rain does not fall within 60 km of the center."

4.3.3 Development and Movement. The triggering mechanism for monsoon depressions is still in dispute and so the various theories advanced to explain their development within the southwest monsoon will not be presented here. However, although the trigger remains undiscovered, Ramage (1971) gives the following favorable preconditions:

(a) The monsoon trough must lie some distance south of the Himalayas, generally along the Ganges Valley, and must protrude over the north end of the Bay of Bengal; and

(b) the vertical circulation over the southern bay (convergent west-southwesterlies overlain by divergent east-northeasterlies) must accelerate.

The resultant increase in low-level cyclonic vorticity south of the monsoon trough is concentrated into a vortex in the trough, leading to massive lifting, release of condensation heat, and circulation intensification.

The favorable preconditions result in generally increased cloudiness over peninsular India and the Bay of Bengal. However, since the triggering mechanism is not clear, satellite observations showing such an increase in cloud cannot be regarded as positive evidence of a monsoon depression (compare Figures C-5 and C-6 in Appendix C). When a monsoon depression is present, however, the accompanying increase in cloudiness makes it difficult to detect movement and position from satellite photographs. Fortunately, since monsoon depressions are confined to the head of the bay, surface observations are of reasonable assistance in locating the existence and center of the system. However, the necessary presence of the monsoon trough tends to mask the comparatively weak surface pressure gradient associated with the depression. A further clue to the impending development of a monsoon depression as a surface circulation feature may be found in the 850 mb chart. Investigations reveal that cyclogenesis first appears at a height of between 2 and 3 km, and the circulation subsequently extends to the surface.

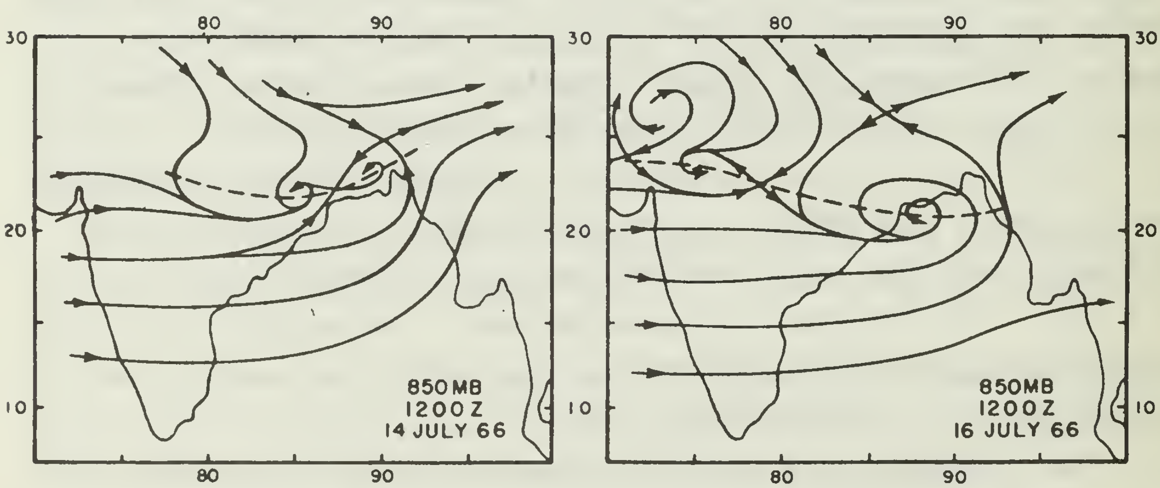


Figure 4-4. Streamline analyses for 850 mb over the Bay of Bengal for 14 and 16 July 1966 showing the southward migration of the monsoon trough line prior to depression formation on 17 July 1967. Monsoon trough position indicated by dashed line (from Atkinson, 1971).

Figure 4-4 shows 850 mb streamline charts for 14 July 66 and 16 July 66. On 14 July the monsoon trough at 850 mb was near its normal position overland. By 16 July the trough had moved southward to lie over the head of the bay (see precondition (a)). On the following day, 17 July 66, a surface depression of 990 mb formed in the trough and moved inland.

During the summer monsoon season, monsoon depressions develop 2 or 3 times per month over the northern part of the Bay of Bengal. They move roughly west-northwestward along the tropospheric mean isotherms or parallel to the flow at 10 - 12 km. According to Ramage (1971), "They generally merge into the monsoon trough over Rajasthan. However, about once in ten years a still-active depression recurves to the north or northeast, giving heavy rain over Kashmir. Recurvature, occurring east of a large amplitude trough in the polar westerlies, accompanies a break in the monsoon, when rains shift north to the sub-Himalayas."

4.4 THE MID-TROPOSPHERIC CYCLONE

4.4.1 Introduction. The second class of large-scale cyclonic circulations which affect the north Indian Ocean (as well as other tropical regions) is that of the mid-tropospheric cyclone; so-called because the circulation first appears in the mid-troposphere although it may subsequently extend downwards and be detectable in the surface pressure pattern.

Two types of mid-tropospheric cyclones have been identified and studied. The first of these affects the eastern portion of the North Pacific and North Atlantic Oceans during the cool season, and is associated with a cut-off pool of cold air from higher latitudes intruding into the tropics or sub-tropics. An example would be the Kona storms of Hawaii. Since these areas lie outside the area of concern of this Handbook, this type of mid-tropospheric cyclone will not be discussed further.

The second type of mid-tropospheric cyclone is that commonly affecting the Arabian Sea near the west coast of India during the southwest monsoon season. They have also been observed over southern Indochina (Krishnamurti and Hawkins, 1969). Their occurrence over the Bay of Bengal appears to be infrequent; however, Ramage (1964) documents a case of a mid-tropospheric cyclone over the bay and so an account of these phenomena will be provided. Their frequency of occurrence may be greater than is reported in the literature. It is hoped that forecasters operating in the Bay of Bengal will be able to recognize such phenomena from the description given and will report details of any such occurrences to the Environmental Prediction Research Facility.

Atkinson (1971) has produced an excellent description of the mid-tropospheric cyclones affecting the Arabian Sea and paragraph 4.2.2 is based on this description. It will be assumed that this description is also applicable to cyclones of this type affecting the Bay of Bengal.

4.4.2 Description and Associated Weather (Based on Atkinson (1971)). Acording to Miller and Keshavamurthy (1968), the mid-tropospheric cyclones affecting the Arabian Sea along the west coast of India occur during the southwest monsoon season. They develop between 700 and 500 mb in the monsoon trough lying across the northeast Arabian Sea and are the major producers of rainfall along the west coast of India.

The mean position of the monsoon trough over India in July at 900 meters and 500 mb is shown in Figure 4-5; this was determined from the resultant wind field. Note that, in the mean, the vertical slope of the monsoon trough over western India and Pakistan is markedly more shallow than over eastern India.

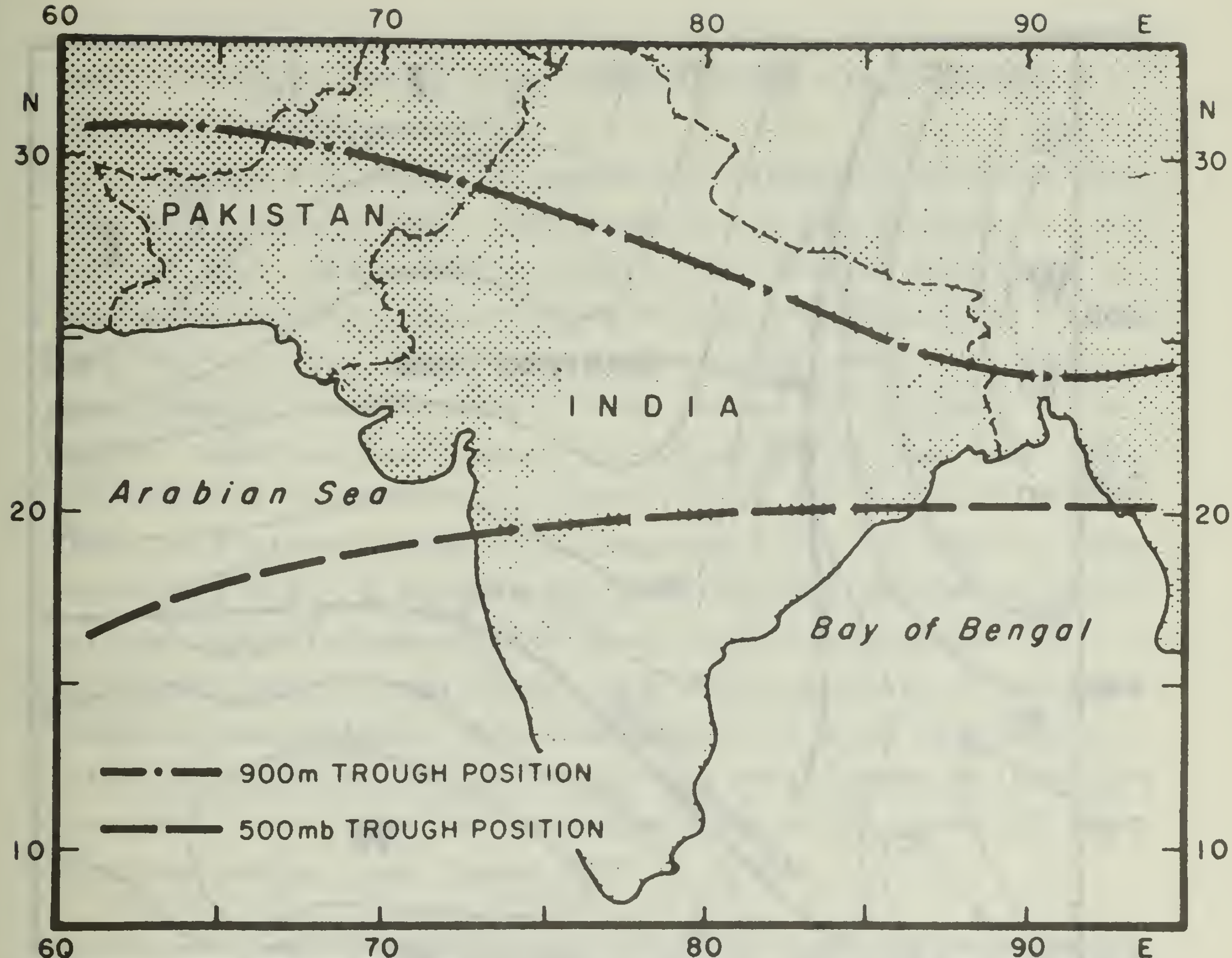


Figure 4-5. Mean July positions of the monsoon trough over India at 900 meters and 500 mb (from Atkinson, 1971).

Figure 4-6 is a north-south cross-section of the resultant wind field in July along western India.

Note that the monsoon trough disappears above 400 mb where a steady easterly regime prevails to the south of the sub-tropical ridge. The tropical easterly jet is evident near 100 mb south of 20N while the mid-latitude westerly maximum occurs north of 35N near the 200 mb level.

It is a fact that during the summer monsoon, surface cyclones are rarely observed over the northeast Arabian Sea and its littoral but occur frequently over the Bay of Bengal. A possible explanation for this difference in weather characteristics of the two regions is offered by the zonal

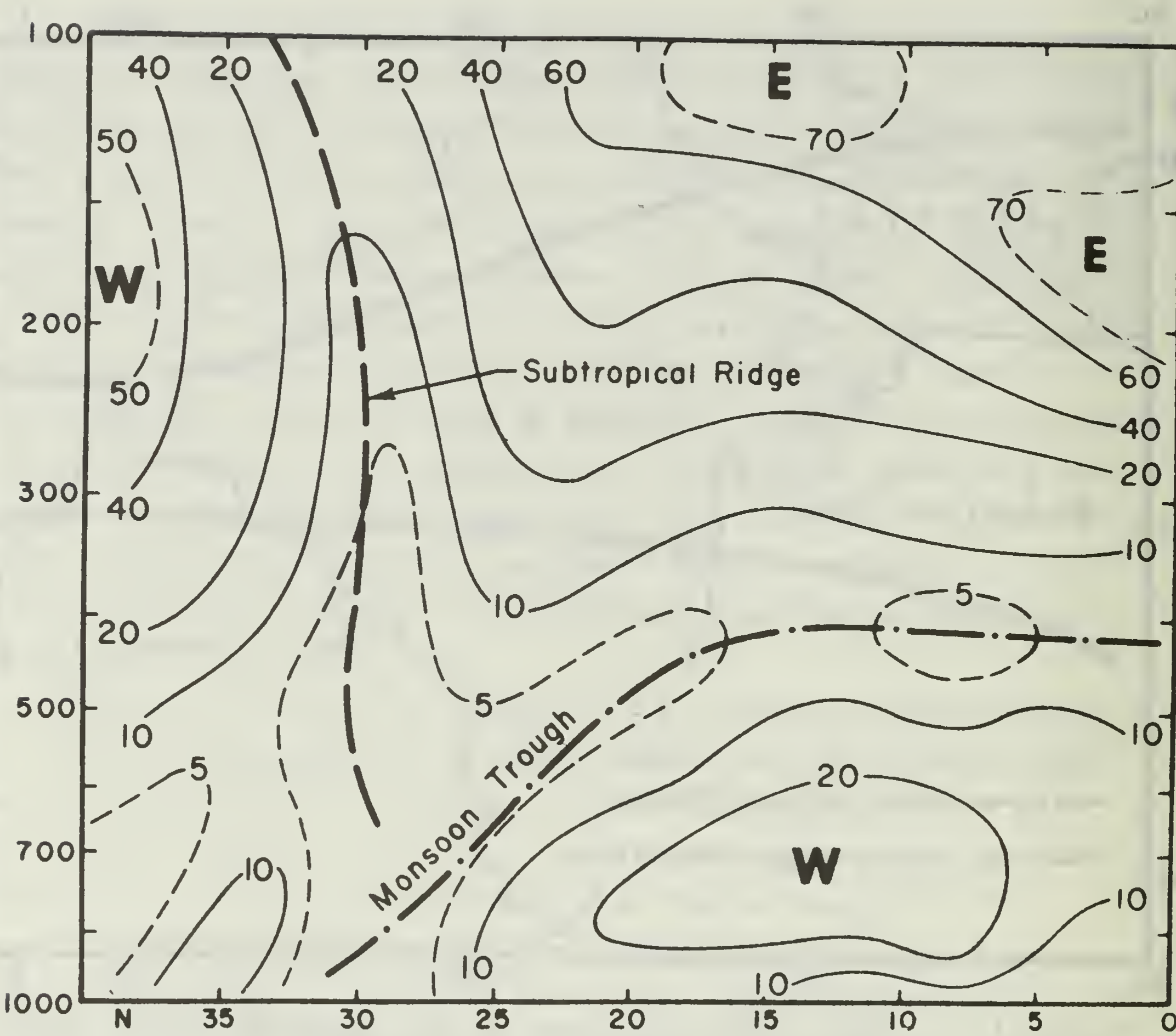


Figure 4-6. North-south cross section of the July resultant wind speeds (knots) and directions (east or west) along western India (from Atkinson, 1971).

variation in monsoon trough structure shown in Figures 4-5 and 4-6. Over the Arabian Sea, mid-tropospheric cyclones are the dominant weather feature during the southwest monsoon and are the cause of most of the summer rains occurring in western India (see Appendix C, Figure C-5). However, over the Bay of Bengal, the dominant weather feature during the summer months is the monsoon depression (see paragraph 4.3).

A persistent mid-tropospheric cyclone occurred near Bombay during the period 1 - 10 July, 1963. This system

was studied in detail and composite wind, pressure, temperature, moisture and weather distributions associated with this system were prepared.

Figure 4-7 shows the composite kinematic analyses for the near-surface (500 - 900 meters) and 600 mb levels. As can be seen, the cyclonic circulation is well developed at 600 mb while the only evidence of the circulation affecting the near-surface layer is the weak trough near the coast. The composite temperature fields showed the cyclone to be colder than the environment at 700 mb and warmer than the environment at 500 mb. A composite of the vertical motion and cloud distribution associated with the cyclone is shown in Figure 4-8. A dynamic explanation (not presented here) may be given to demonstrate that such mid-tropospheric cyclones cannot be maintained in a steady state without cumulus convection. This explanation is also consistent with the observed evidence that the most severe weather and greatest vertical cloud development is to the west of the cyclone center (see Figure 4-8).

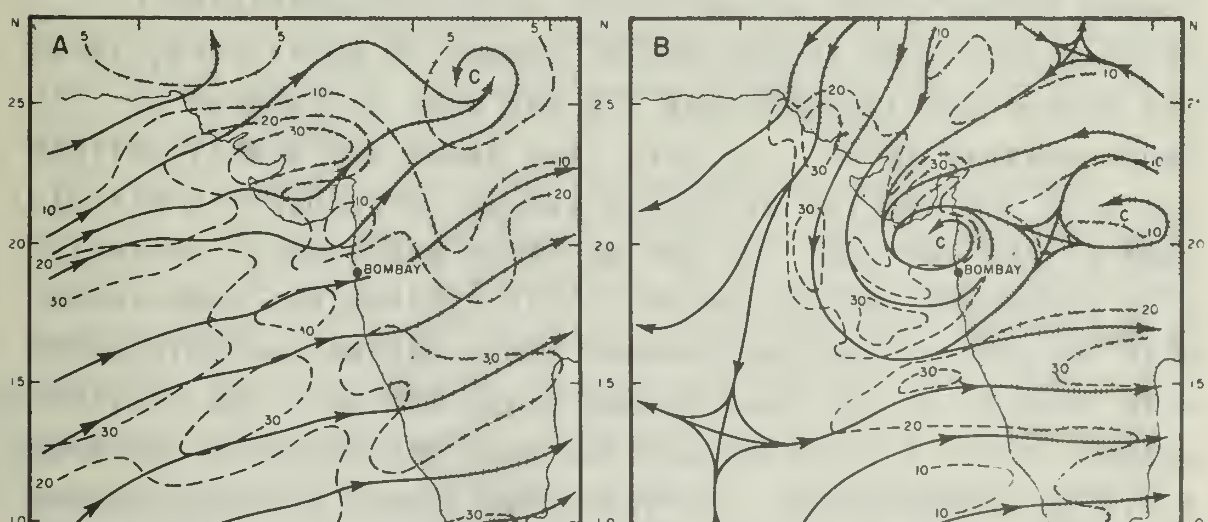


Figure 4-7. Composite kinematic analyses for: (A) a near-surface layer (500-900 meters), and (B) the 600-mb level showing a well developed mid-tropospheric cyclone over western India during July 1963 (from Atkinson 1971).

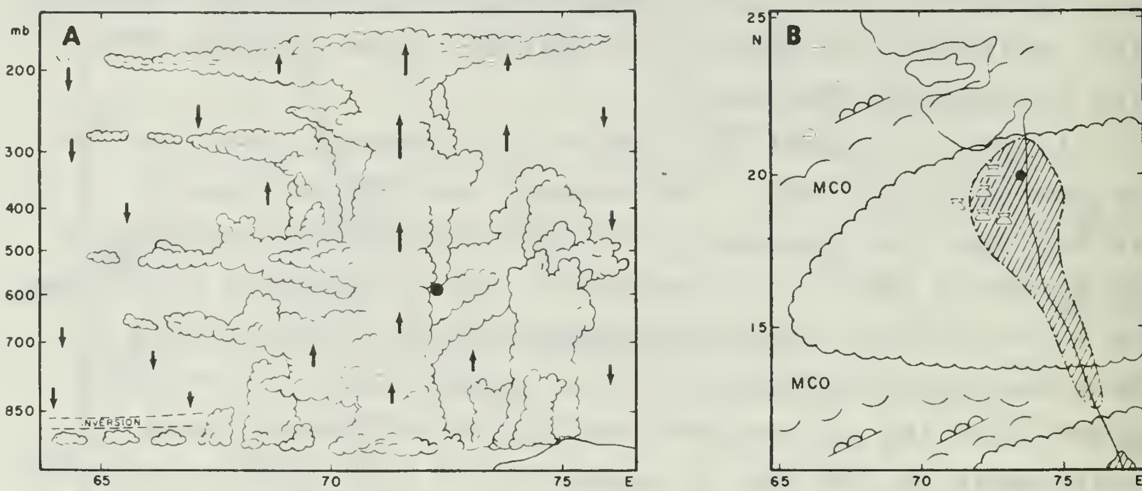
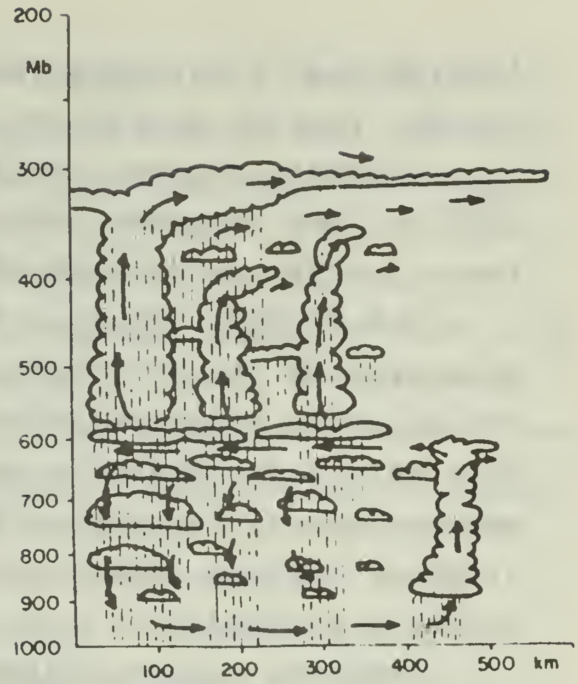


Figure 4-8. (A) East-west vertical cross section of clouds and vertical motion, and (B) horizontal distribution of cloudiness and rainfall around the mid-tropospheric cyclone in Figure 4-7. The 600-mb position of the cyclone center is shown by a heavy dot. Arrows in (A) show relative vertical-motion field computed from composite wind analyses. Lined area in (B) shows extent of rainfall exceeding 4 cm/day, stippled areas outline broken to overcast middle or high cloud, and broken areas show extent of broken to overcast low clouds (from Atkinson 1971).

4.4.3 <u>A Mid-Tropospheric Cylone in the Bay of Bengal</u>. Ramage (1964) gives a case study of a mid-tropospheric cyclone occurring in the Bay of Bengal in early June, 1963. The center was located near 11N 95E with a diameter of approximately 50 km. In this case there was a well defined cyclonic circulation at 500 mb but no corresponding circulation at the surface. At 200 mb there was general easterly flow above the 500 mb center. This cyclone was warm-cored with respect to the environment above 650 mb and cold-cored with respect to the environment below 650 mb. The similarity between this circulation and the type discussed in paragraph 4.4.2 is unmistakable. A "tentative model" for the western sector of this particular system was constructed by Ramage (see Figure 4-9) with the warning that the model for the eastern sector may be markedly different. In this system there was no subsidence inversion near the 850 mb level

Figure 4-9. Schematic radial cross-section westward from the center of a monsoon cyclone. Arrows roughly indicate the sense but not the magnitude of radial and vertical motions (from Ramage, 1964).



(compare with Figure 4-8) and Ramage concluded that descending air was reaching the surface and resulting in a zone of low-level convergence between the outflowing air and the undisturbed environment.

4.5 THE TROPICAL CYCLONE

4.5.1 Introduction. Tropical cyclones are the most dangerous meteorological phenomena encountered by shipping, and those tropical cyclones to be found in the Bay of Bengal are no exception.

This section presents and discusses the tropical cyclones of the Bay of Bengal based on the statistics and theory of "conventional" meteorology as well as satellite meteorology. That information concerned with satellites is based on the research of Sadler and Gidley (1973) who, working under contract to the Environmental Prediction Research Facility, prepared a satellite-oriented study of the tropical cyclones of the North Indian Ocean. This publication (EPRF Technical Paper No. 2-73) may be obtained from EPRF. Although this Handbook is concerned primarily with the Bay of Bengal some statistical information on the

Arabian Sea is included for comparison and, in addition, so are the results of Sadler and Gidley (1973) for that area.

Appendix A gives tropical cyclone tracks for the years 1877 to 1960 together with a discussion of the track characteristics for each month of the year.

4.5.2 Definitions. Atkinson (1971) points out, "A knowledge of the different classification systems is mandatory for accurate interpretation or comparison of tropical cyclone forecasts and statistics prepared by the various national meteorological services. Adoption of a universal system of tropical cyclone classification would eliminate the current semantic confusion."

Tropical cyclone intensities in the North Indian Ocean area are defined by the Indian Meteorological Department as:

Tropical Depression	- Winds Less Than 34 Knots
Moderate Cyclonic Storm	- Winds of 34 - 47 Knots
Severe Cyclonic Storm	- Winds of 48 - 63 Knots
Severe Cyclonic Storm With a Core of Hurricane Winds	- Winds Greater Than 63 Knots

It will be noted that no attempt is made to separate the monsoon depressions of summer (see paragraph 4.3) from cyclonic systems of depression intensity at other times of the year; the latter are very much more likely to intensify into severe cyclonic storms and beyond. Winds associated with monsoon depressions sometimes reach gale force (see paragraph 4.3.2) and therefore are labeled cyclonic storms. However, such systems are extremely unlikely to intensify further.

Statistics available for the Bay of Bengal normally use two categories of intensity for tropical cyclones. These are the tropical depression with winds of 33 kt or less, and the cyclonic storm with winds of 34 kt or more.

This terminology will normally be used in this Handbook when referring to the Bay of Bengal or Arabian Sea. However Sadler and Gidley (1973) also give the frequency of storms reaching hurricane force based on 4 to 5 years of satellite data. They use three classifications: depression, cyclonic storm, and hurricane. The term "tropical storm" will be used more generally to refer to a tropical cyclonic disturbance with winds of 34 kt or more, including typhoons and hurricanes.

4.5.3 Tropical Cyclone Statistics for the Bay of Bengal. Study of the statistics in the literature relevant to the Bay of Bengal reveals discrepancies. For example, Gray (1968), who uses 35 kt as the minimum wind speed for a cyclonic storm, gives 6 as the average number of cyclonic storms in the Bay of Bengal per year. However, Rai Sircar (1958), considering the 61-year period between 1890 and 1950, states that there were 288 cyclonic storms; this represents an average figure of less than 5 per year. Atkinson (1971) states that during the 60-year period 1891 to 1950 there was an average of 6 cyclonic storms but also states that for the 20-year period 1948 to 1967 the average figure was less than 4. He suggests that the decrease is due to the fact that "many of the tropical depressions occurring in the Bay of Bengal in the earlier years during the southwest monsoon season (Jun - Sep) were probably classified as tropical storms." On the other hand, a study by Sadler and Gidley (1973) of 4 or 5 years' satellite data revealed a marked increase in the number of cyclonic systems attaining an intensity greater than 34 kt as compared with pre-satellite data.

Atkinson (1971) states that his statistics are based on Gray's paper, some of Gray's data being modified slightly from more recent information. Atkinson's values are used in this section, but the operational meteorologist should

be aware that, for example, probability values for the frequency of occurrence of cyclonic storms in the Bay of Bengal will vary according to source. The wideness of this variation is illustrated by Gray's 6 storms per year, the 3.4 storms per year of Atkinson, and the apparent increase in storm frequency for certain months discovered by Sadler and Gidley in their satellite study (see paragraph 4.5.4).

Table 4-1 shows the mean monthly and annual frequencies for cyclonic depressions and storms in the Bay of Bengal and the Arabian Sea. About 4% of the global total of tropical cyclones of cyclonic storm intensity or higher occur in the Bay of Bengal; the corresponding figure for the Arabian Sea is 1%. Table 4-1 should be compared with Table 4-3, the latter being based on data covering the period 1891 - 1960.

Table 4-1. Mean monthly and annual frequency of tropical cyclones (from Atkinson, 1971).

	J	F	M	A	M	J	J	A	S	O	N	D	TOTAL
						Bay of Bengal (1948-67)							
CD	0.2	0.1	0	0.2	0.5	1.0	1.6	1.4	1.7	1.2	0.2	0.1	8.2
CS	0.1	0	0	0.1	0.7	0.1	0.1	0.1	0.4	0.8	0.7	0.5	3.6
						Arabian Sea (1890-67)							
CD	0.1	*	*	*	0.1	0.2	0.1	*	0.1	0.3	0.2	0.1	1.2
CS	*	0	0	0.1	0.2	0.2	*	*	0.1	0.2	0.2	0.1	1.1

CD: Cyclonic Depression CS: Cyclonic Storm or Hurricane *: Frequency <0.05%

The values for the Bay of Bengal plotted in Figure 4-10 clearly show the bi-modal distribution of cyclonic storms. The peak in cyclonic storm frequency during May occurs during the spring transition period while the near-equatorial trough is migrating northward. The second peak occurs in the fall transition period as the trough retreats southward from the head of the bay. An explanation for this bi-modal distribution is given in paragraph 4.5.5.

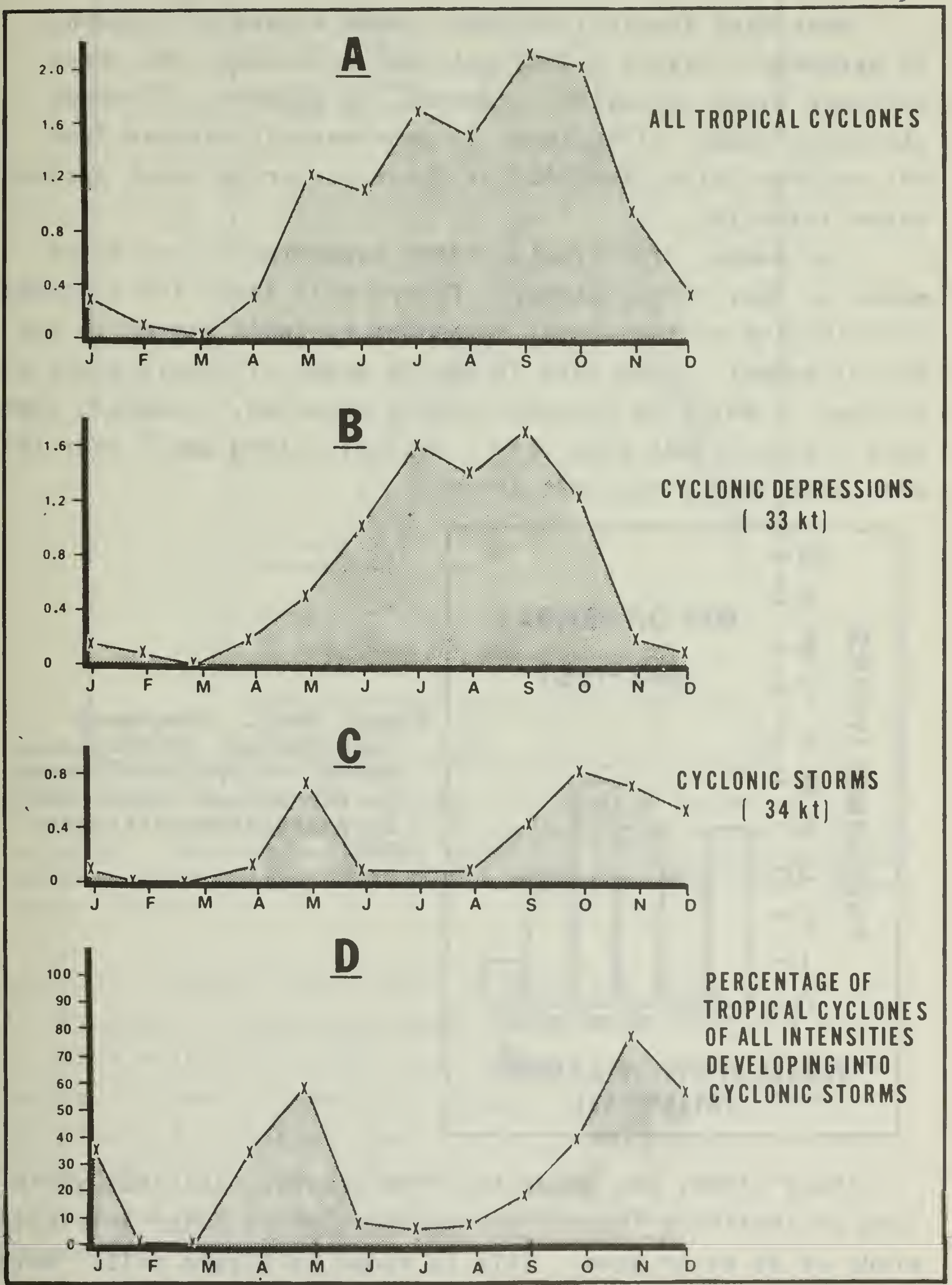


Figure 4-10. Mean monthly distribution of tropical cyclones in the Bay of Bengal.

Note that tropical cyclones reach a peak in frequency in September (Figure 4-10A) but that only about 20% reach cyclonic storm intensity. However, in November, although the total number of cyclones is considerably reduced from the maximum value, some 80% of those occurring reach cyclonic storm intensity.

The number of cyclonic storms occurring in any given month or year varies widely. Figure 4-11 shows the frequency distribution of the annual number of cyclonic storms in the Bay of Bengal. Note that in the 20 years of record there was no year in which no cyclonic storms occurred. However, there were 4 years (20%) with only 1 cyclonic storm and 1 year (5%) with more than 5 cyclonic storms.

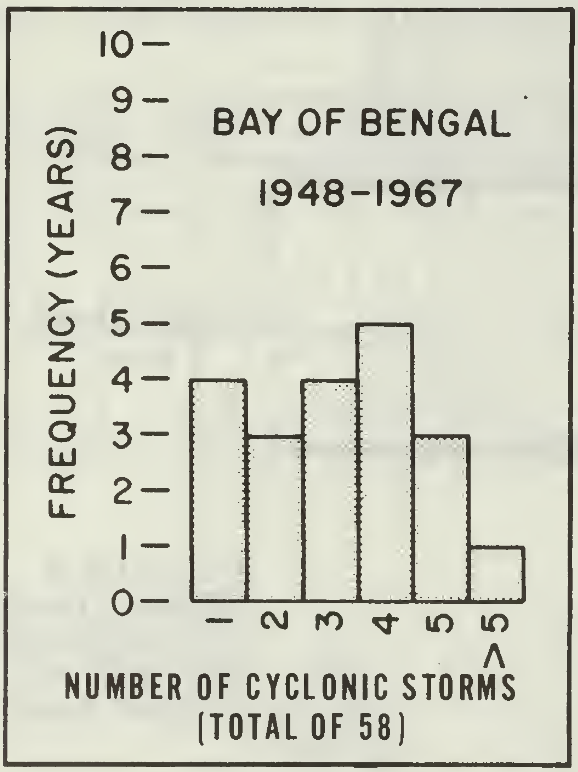


Figure 4-11. Frequency distribution of the annual number of cyclonic storms in the Bay of Bengal for 20 years (from Atkinson, 1971).

Gray (1968) has determined the seasonal latitude variation of initially located disturbances which later developed winds of 35 kt or more. This is shown in Figure 4-12. Note that the latitudinal variation for the northern Indian Ocean

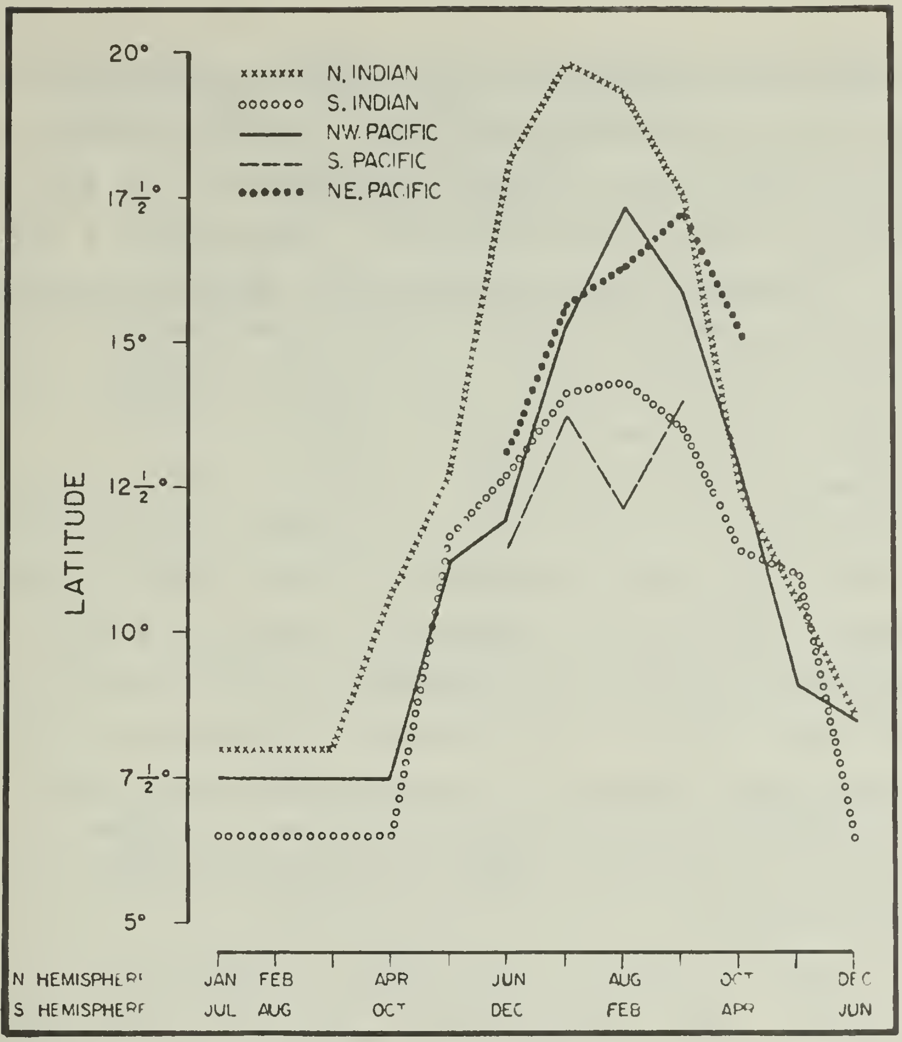


Figure 4-12. Seasonal latitude variation of point of original disturbances which later developed winds of 35 kt or more. The curve for the northern Indian Ocean includes monsoon depressions meeting the windspeed criterion (from Gray, 1968).

should be used with due regard to the fact that, during the earlier part of the record used, the probability of a cyclonic storm being first detected increases as it moves north towards the head of the bay. Figure 4-12 may be compared with Figure 4-2 showing that the periods of discontinuous troughs (May/June and September/October) are also the periods during which the initial latitude of the disturbances is changed most rapidly.

Appendix A contains the tracks of tropical cyclonic storms in the Bay of Bengal during the period 1877 to 1960,

together with a discussion of the monthly characteristics. This information was extracted from "Tracks of Storms and Depressions in the Bay of Bengal and Arabian Sea 1877-1960" published by the India Meteorological Department (1964).

4.5.4 Tropical Cyclone Statistics Based on Satellite Data. This paragraph presents some of the results obtained by Sadler and Gidley (1973). For complete details the origina publication should be consulted.

The study used photographs from polar orbiting meteorological satellites to obtain the frequency and tracks of depressions, storms and hurricanes in the North Indian Ocean from November 1966 through December 1970 plus October 1971. The guidelines of Hubert and Timchalk (1969) were followed in estimating the intensity of systems. No data were extracted for July and August and, in June and September, all of the systems forming in the Bay of Bengal north of 19N were excluded. This procedure eliminated monsoon depressions from the statistics.

The results of Sadler and Gidley, admittedly based on a small sample, show a marked increase in the frequency of cyclonic circulations when compared with data from the pre-satellite era. The operational forecaster in the Bay of Bengal should be aware of the possibility that tropical cyclones may occur more frequently than indicated by Table 4-1. However, the statistical sample is too small as yet to make a definitive statement.

Table 4-2 shows the number of depressions, cyclonic storms, and hurricanes by area and by month. If a system tracked from the Bay of Bengal into the Arabian Sea, it was counted in each area with its appropriate intensity category. However, such a circulation was counted only once, under its most intense category, in the North Indian Ocean summary.

Table 4-3 shows the monthly frequency of tropical cyclones attaining tropical storm intensity or greater. Two sets of data are compared:

Table 4-2. Number of depressions, cyclonic storms and hurricanes based on satellite data (Sadler and Gidley, 1973).

Month	Period	Bay of Bengal			Arabian Sea			North Indian Ocean		
		Dep.	C.S.	Hur.	Dep.	C.S.	Hur.	Dep.	C.S.	Hur.
January	1967-1970	5	0	0	2	0	0	7	0	0
February	1967-1970	1	0	0	2	0	0	2	0	0
March	1967-1970	2	0	0	0	0	0	2	0	0
April	1967-1970	0	0	0	0	0	0	0	0	0
May	1967-1970	3	2	2	1	0	1	3	2	3
June	1967-1970	0	0	0	2	0	0	2	0	0
September	1967-1970	2	1	0	0	0	0	2	1	0
October	1967-1971	5	5	4	7	0	1	9	5	5
November	1966-1970	3	1	6	3	3	1	5	3	6
December	1966-1970	1	3	2	4	0	0	2	3	2
Total		22	12	14	21	3	3	34	14	16

Table 4-3. Frequency of tropical cyclones attaining storm or hurricane intensity--number per month (Sadler and Gidley, 1973).

Month	Bay of Bengal		Arabian Sea		North Indian Ocean	
	1891-1960	1967-* 1970	1891-1960	1967-* 1970	1891-1960	1967-* 1970
January	.05	0	.03	0	.06	0
February	.01	0	0	0	.01	0
March	.05	0	0	0	.06	0
April	.26	0	.07	0	.33	0
May	.40	1.0	.18	.25	.58	1.25
June	N/C	0	N/C	0	N/C	
September	N/C	.25	N/C	0	N/C	.25
October (+ 1971)	.76	1.80	.24	.20	.97	2.00
November (+ 1966)	.80	1.60	.30	.80	1.03	1.80
December (+ 1966)	.37	1.00	.04	0	0.40	1,00
Jan-May and Oct-Dec	2.70	5.42	.86	1.25	3.44	6.05

N/C not comparable

* Based on satellite data

a. Frequencies based on the India Meteorlogical Service climatology covering the period 1891-1960,

b. The results obtained by Sadler and Gidley based on satellite data.

Table 4-3 should be compared with Table 4-1.

Considering only the months of maximum cyclonic storm activity (May, October, November), Tables 4-1 and 4-3 give the following totals:

Bay of Bengal		
Atkinson	:	2.2
India Meteorological Service	:	2.0
Sadler and Gidley	:	4.4
Arabian Sea		
Atkinson	:	0.6
India Meteorological Service	:	0.7
Sadler and Gidley	:	1.3

The data sample available to Sadler and Gidley was small. Therefore, it would seem probable that part of the very marked observed increase in cyclonic storm frequency was due to the natural variability in numbers of these phenomena, and part was caused by a real increase due to the improved observational techniques offered by satellites. It must be concluded that the "true" statistics for the Bay of Bengal remain in some doubt.

Sadler and Gidley found that the average speed of cyclones during the depression stage was 8.3kt, increasing slightly to 8.5kt for cyclonic storms and hurricanes.

4.5.5 Cyclonic Storm Development. According to Palmen and Newton (1969), "The most difficult problem in the theory of tropical cyclones is to account for the initial formation. Many writers (e.g., Riehl) have pointed out that the development is not spontaneous; rather, intense storms always evolve from some disturbance of lesser intensity, which may have been in existence for a long time."

According to Ramage (1971), Palmen listed the following prerequisites for the development of an intense tropical cyclone:

> *(1) "Sufficiently large sea or ocean areas with the temperature of the sea surface so high (above 26 to 27C) that an air mass lifted from the lowest layers of the atmosphere (with about the same temperature as the sea) and expanded adiabatically with condensation remains considerably warmer than the surrounding undisturbed atmosphere at least up to a level of about 12 km. [Some evidence suggests that the absolute value of the sea-surface temperature may not be critical, but rather that the gradient of sea-surface temperature should be small over distances of several hundreds of kilometers.]*
>
> *(1) "The value of the Coriolis parameter larger than a certain minimum value, thus excluding a belt of the width of about 5 to 8 deg lat on both sides of the equator.*
>
> *(3) "Weak vertical wind shear in the basic current, thus limiting formation to latitudes far equatorwards of the subtropical jet stream."*
>
> *Riehl (1954) listed these additional requirements:*
>
> *(4) A preexisting low-level disturbance (areas of bad weather and relatively low pressure).[1]*
>
> *(5) Upper-tropospheric outflow above the surface disturbance.*

The space and time variations of tropical cyclonic disturbances observed in the Bay of Bengal may be reasonably explained in terms of these prerequisites. Prerequisite 5 will not be invoked as some authors, e.g., Gray (1968), consider that divergence in the upper troposphere is a result, rather than a cause, of low level convergence. (Other eminent authorities, e.g., Ramage, do not agree with this view). In addition, study of the mean monthly sea surface temperature charts given in Appendix B shows that prerequisite 1 is normally satisfied in the Bay of Bengal.

---

[1]This implies low level cyclonic wind shear and associated frictional convergence.

December through March

This is the time of the northeast monsoon. Appendix B shows that sea surface temperatures are at a minimum in the bay although, even so, the temperature does not fall significantly below 80F (27C). Identifying the near-equatorial trough and its associated convergence zone (paragraphs 4.2.3 and 4.2.4) with prerequisite 4, and considering Figure 4-2, one would anticipate that cyclonic disturbances would intensify in the far south of the Bay of Bengal. This is supported by prerequisite 3, which is concerned with wind shear (see Figure 4-13A). However, the low value of the Coriolis parameter in this area (prerequisite 2) would tend to prevent the intensification of cyclonic disturbances. Thus, considering all the factors, it would be expected that intensifying disturbances would be rare during these months and would be confined to the southern part of the bay, intensifying only when short-term variations in the position of the near-equatorial trough allowed the trough to move significantly to the north of its mean position. However, if such a variation did occur, in view of the other prerequisites satisfied, one would anticipate that a fairly high percentage of initially weak disturbances would intensify into cyclonic storms. This is supported by Figure 4-10(D). However, it should be pointed out that the difficulty of identifying weak circulations in this area would also give a similar result.

June through September

This is the time of the southwest monsoon. Appendix B shows that the sea surface temperature is sufficiently high at all times to satisfy prerequisite 1. Prerequisite 2 is certainly satisfied, as is prerequisite 4, since the monsoon trough frequently lies across the head of the Bay of Bengal at this time of the year. One would therefore expect a large number of cyclonic disturbances to occur and, indeed, this is

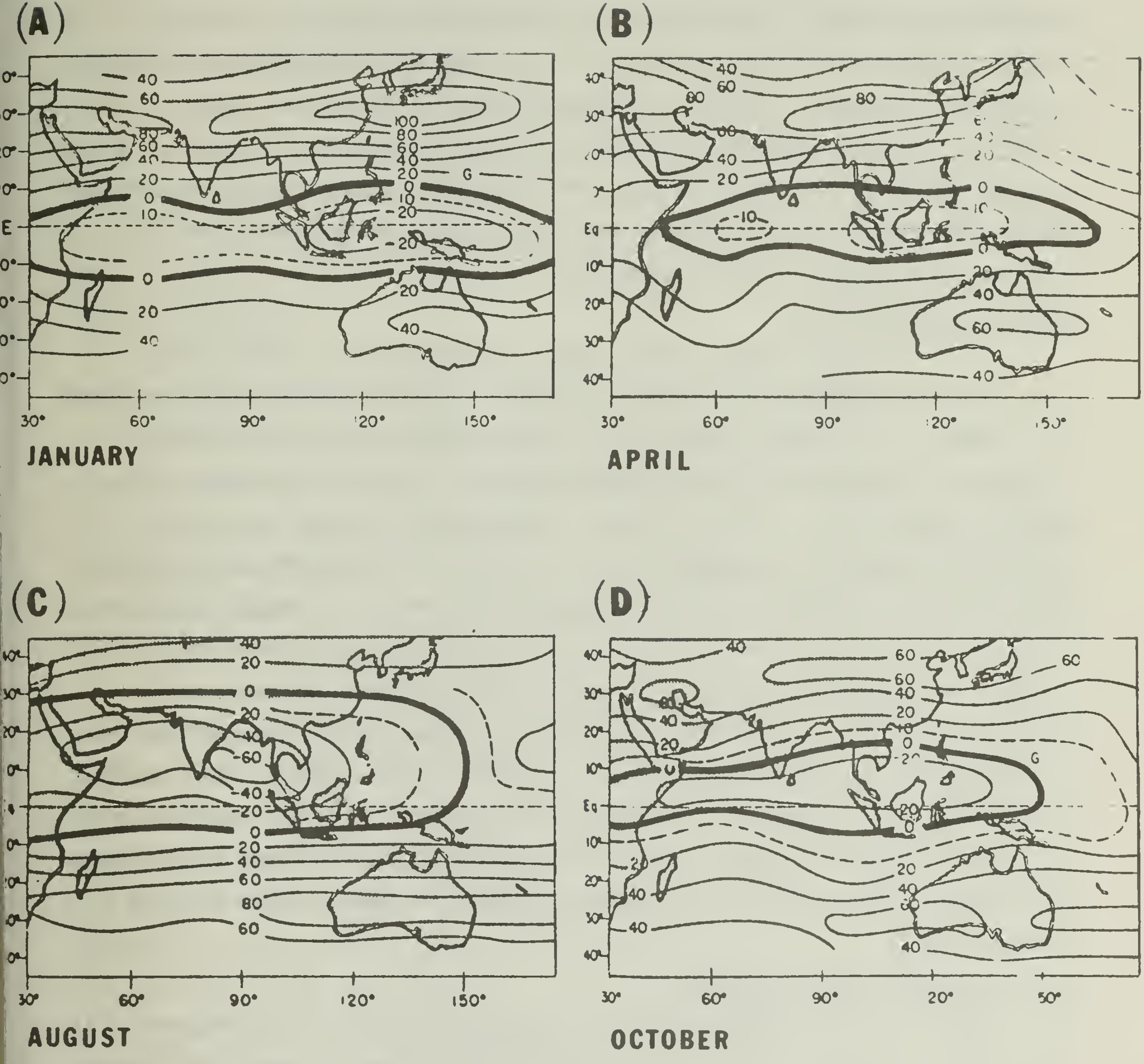


Figure 4-13. Climatological average for four months of the zonal vertical wind shear between 200 mb and 850 mb (from Gray, 1968). Note: Positve values indicate zonal wind at 200 mb is stronger from the west or weaker from the east than the zonal wind at 850 mb.

so (see Figure 4-10A). However, Figure 4-13C shows that the vertical shear during the southwest monsoon is high (see prerequisite 3). One would thus expect that, out of the large number of disturbances, very few would intensify into cyclonic storms. This is supported by Figures 4-10B, C, and D. These disturbances, which fail to intensify into cyclonic storms due to the high value of vertical shear and the proximity of land to the north, are the monsoon depressions of the summer season (see paragraph 4.3).

April through May

This is the transition period during the changeover from the northeast monsoon of winter to the southwest monsoon of summer. At this time of the year the near-equatorial trough is advancing northwards albeit discontinuously (see paragraph 4.2.3). The trough is not as intense as the monsoon trough of summer and so fewer initial disturbances are likely. The various figures show that prerequisites 1, 2 and 4 are satisfied and the vertical shear is not yet excessive, particularly in the southern part of the bay. One would thus expect the number of initial disturbances to be less than for the summer months, but that a high percentage would develop into cyclonic storms, thus forming a peak in cyclonic storm activity between the winter and summer monsoons. That this is indeed so can be seen from Figure 4-10C and D.

October through November

This is the transition period between the southwest monsoon of summer and the monsoon of winter. The still very active (but weakening) trough retreats discontinuously southwards across the bay (see Figure 4-2). Sea surface temperatures are generally in excess of 80F thus satisfying prerequisite 1. Prerequisites 2 and 3 are also satisfied. Thus one would expect a large number of cyclonic disturbances to occur, and that a very high percentage of these would

intensify into cyclonic storms (see Figure 4-10). The increased number of cyclonic storms, compared with summer and winter, forms another peak in cyclonic storm frequency as shown by Figure 4-10D.

It can thus be seen that the observed characteristics of tropical cyclonic disturbances in the Bay of Bengal can be interpreted and explained in terms of the prerequisites listed and the supporting observational data. In particular, the bi-modal distribution of cyclonic storm frequency can be explained.

4.6 GALES, STRONG WINDS, SQUALLS, AND THUNDERSTORMS

Figure 4-14 shows surface wind roses for each month of the year for an area in the middle of the Bay of Bengal. This area is shown in Appendix B as "Area A" in Figure B-2(a) and other surface wind roses are contained in Figures B-2(b) through B-2(f). A description of the information provided in the wind roses is given in the introduction to Appendix B.

These wind roses are based on ships' observations and should be used with caution for two reasons. Firstly, ships endeavor to avoid strong winds, thus, in general, biassing data towards lighter winds. Secondly, a small data sample can give very misleading results. For example, with only a few observations contributing towards average conditions, several reports from one ship experiencing gale force winds can distort the statistics. It is suspected that this is the case for "Area A" where, with only about 200 observations per month, the percentage frequency of gale observations for September is given as 5.

With these reservations in mind, Figure 4-15 shows the monthly distribution of strong ($\geq$22kt) and gale force (34kt) winds; this information was extracted from Figure 4-14 which, in turn, was extracted from NAVAER-51C-530 (U. S. Navy, 1957). As can be seen, the winter monsoon is most intense in December

AREA "A"

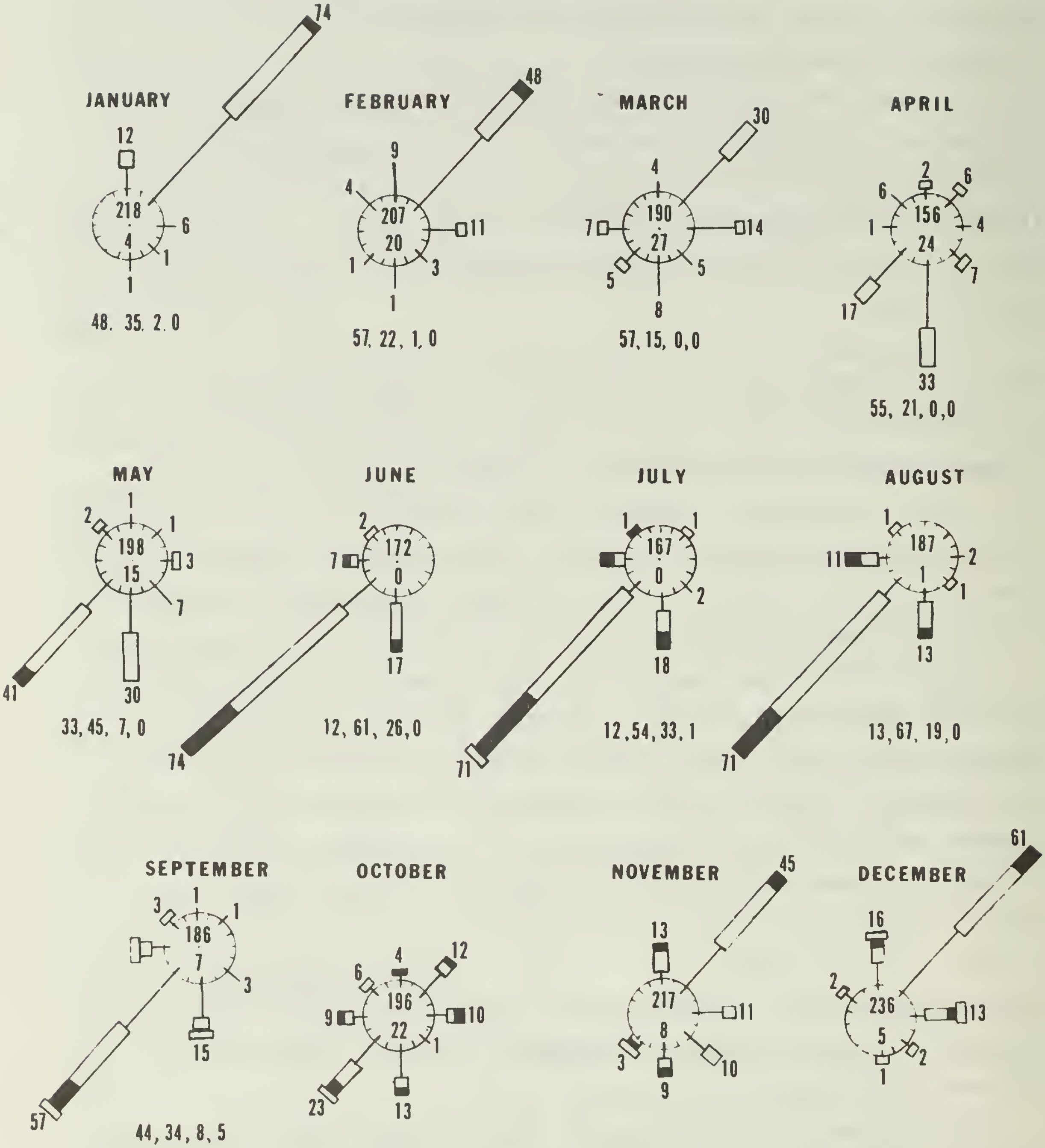
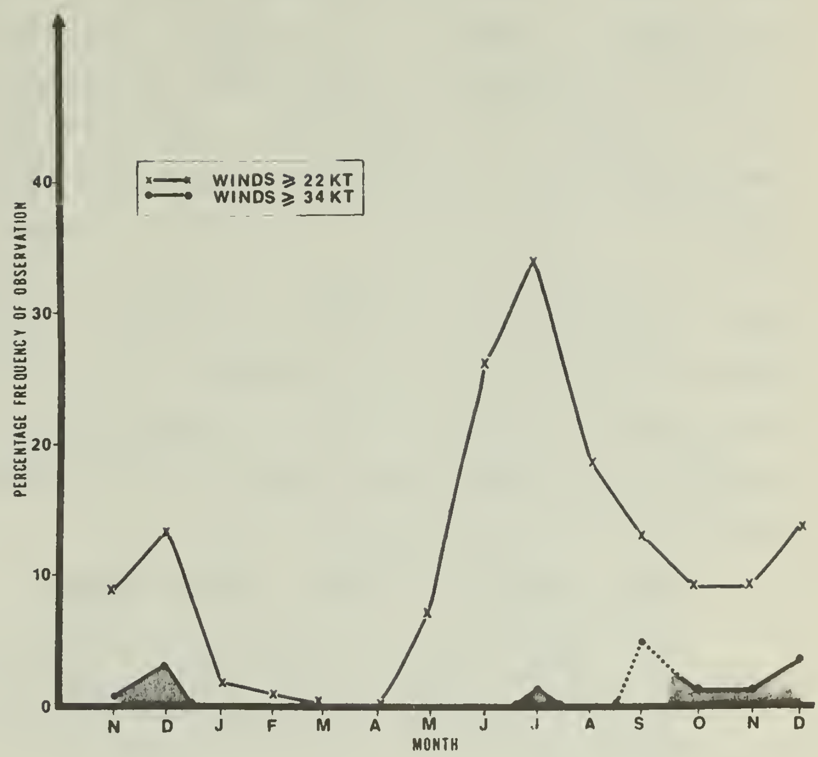


Figure 4-14. Monthly surface wind roses.

Figure 4-15. Monthly distribution of strong winds in the Bay of Bengal.



while the summer monsoon is at its greatest intensity in July. The frequency of gales in September is unlikely and has, therefore, been shown as a dotted line. See also the climatic summaries for areas "A" and "B" given in Tables 6-1 and 6-2.

Strong and gale force winds, even hurricane force winds, may be experienced in squalls. If feasible, it is suggested that radar be used to detect and track these squalls and to provide short-term forecasts and warnings.

Those squalls which occur within about 100 miles of the coasts of Burma, Bengal, and Orissa are called "Nor'westers" (see Figure C-2, Appendix C) A description of these is given in the following paragraphs. However, other squalls may occur over the Bay of Bengal, especially during the spring transition,

and dangerously strong winds may be experienced even when there are no cyclonic storms in the vicinity. The seasonal variation of squalls is further discussed in section 6. The following paragraphs have been extracted from "Weather in the Indian Ocean" (Air Ministry, Met. Office, 1943). The graphic description provided of the wind and weather experienced in squalls encountered in the Bay of Bengal, although old, should be sufficient to indicate to the operational forecaster the need to be aware of these phenomena, and the need to provide timely warnings to the Command. It will be noted that wind strengths in the following paragraphs are given in Beaufort force. An abbreviated table for converting to wind speed in knots is given in Appendix D.

From "Weather in the Indian Ocean"

"The S.S. Matheran gives the following account of a heavy squall which was experienced on November 23, 1937 whilst in the vicinity of the Gulf of Mannar, south of Cape Comorin, in approximate position 6° 36'N., 77° 21'E:

"At 0205 a heavy squall commenced. Wind backed suddenly from ESE. to NE. and freshened to a strong breeze. About 0210 the wind backed to NNE. and blew with hurricane force with torrential rain for about two minutes, when the wind fell away to calm for one minute, the rain continuing as before. The wind then hauled to ENE. and blew steadily from that direction, force 4, rain moderating. Vivid forked lightning and thunder accompanied the squall, which had been threatening for over two hours. Rain continued with moderate ENE. wind until 0400 and during the passage of the squall the barometer pumped violently."

On November 25, 1937 the same ship experienced another violent squall in the Bay of Bengal in approximate position 13° 12' N., 84° 41' E.

At 2132 a violent squall commenced. Wind hauled from NNE. to ENE. and blew with hurricane force, which continued to 2144. During this time torrential rain fell; visibility at the very best was 100 feet. Vivid continuous lightning and thunder accompanied

the squall. At 2144 the wind eased to a gentle breeze, rain continuing as before. Rain suddently ceased, wind backed to NNE. and blew steadily force 5. The barometer, which had been steady for the past 4 hours, also remained quite steady during and after the squall. Ten minutes after the squall had passed the ship passed through a warm current of air which lasted three minutes, after which the temperature was again normal at 76°F. In the evening masses of cumulonimbus clouds could be seen banking up in the NE."

A "Nor'wester" is the name given to a severe type of thunderstorm, accompanied by strong squalls, which occurs occasionally in Bengal and neighbouring regions during the hot weather. They derive their name from the fact that they usually approach from the north-west, although squalls from north and north-east are not unknown. The storms are locally described as "Kal-Baisakhi" or the "fateful thing" of the month of Baisakh (April 15 - May 15). Although the nor'wester season is generally regarded as extending over the months of March, April and May, nor'wester squalls have been experienced in the latter half of February or as late as the middle of June. The arrival of the SW. monsoon puts an end to the storms.

"Nor'westers" may occasionally attain the intensity of a tornado and a few may actually develop into real tornadoes. They sometimes extend to about 100 miles out to sea off the coasts of Burma, Bengal and Orissa.

The first sign of these storms is a low bank of dark clouds in the north-west the upper outline of which has the appearance of an arch. It approaches at first slowly and then more rapidly and arrives with a strong gust or squall. There is, frequently, thunder and lightning followed by downpours of rain and sometimes hail which is driven by the strong winds. On some occasions the winds blow with almost hurricane force. The greatest speed of the wind recorded in one of these storms is 100 knots.

A well known characteristic of "Nor'westers", especially in April and May, is that they tend to occur in spells, sometimes setting in on four or five consecutive days at about the same time and place.

There is no information about the frequency of occurrence of "Nor'westers" over the sea areas of the Bay of Bengal and even over land it is difficult to give an estimate of the frequency of typical "Nor'westers," as a clear distinction between thunderstorms and "Nor'westers" cannot be made. At Calcutta, the frequency of thunderstorms of any type based on 27 years' data is 2•2 in March, 4•7 in April and 6•1 in May.

These storms almost always occur in the afternoon or evening towards the end of a close, warm day, although they have been known to occur sometimes at other times of the day; they rarely last more than three or four hours and are generally followed by cool and clear weather. At Calcutta they usually occur about or just after sunset. The following is a description of a severe "Nor'wester" that occurred there:

"At Calcutta, the wind was blowing from S. or SW. until 1600 (local time) and had been gusty since noon. At 1600 the wind died down almost to a calm but fifteen minutes later a sudden gust sprang up from the north and reached its maximum speed of about 26 knots in the next few minutes. This was short lived and the wind again dropped and backed slowly to south. At 1645 the wind began once more to veer to the north and increase in speed; shortly after 1700 there was gale from SW. which attained a wind speed of 52 knots at 1705. This whole gale lasted fortunately for only about three minutes and was followed by a few gusts of 9 to 13 knots till about 1745. The accompanying rainfall amounted to 24 mm. (0•93 in.). This storm was extremely localized and affected only the southern portions of Calcutta; in spite of its short duration, however, it did considerable damage to shipping in the river and also a large number of trees were blown down on shore."

Although "Nor'westers" are not normally experienced so early in the year, H.M.S. Norfolk experienced a "blow" characteristic of a "Nor'wester" at Calcutta on the night of March 1 and 2, 1939 and gave the following description of it:-

"On the evening of the 1st, the sky began to cloud over from the north-west with some thick stratus or cirrostratus. The wind which had been light from SW. by W., became gusty and shifted to W. The barograph showed a slight unsteadiness, which might have

been due to the gusting of the wind past the instrument, but at 2130 it showed a sudden rise of pressure. Frequent flashes of lightning were observed.

"At midnight the wind became squally and appeared to be from NW. The barograph by this time was falling sharply with a jerky trace. The sky was 7 tenths covered with what appeared to be sheet cloud. At 0130 the wind increased suddenly, followed by a heavy rainstorm which lasted for about 20 minutes and then suddenly ceased. The wind died down, becoming gusty, with a light shower or two later in the night. By the following morning the sky had cleared and the wind had gone back to SW. by W."

The barograph gave little indication of this "blow", although it showed the pressure for the past few days to have been below the normal for the month.

This next description is of a "Nor'wester" experienced by a ship in the Bay of Bengal; it is included here to show that these storms when encountered at sea are very similar to those that occur over the land; the times quoted are ship's time.

"On April 15th, 1928 the S.S. Stockwell encountered a "Nor'wester" in position 17° 34' N., 84° 50' E., about eighty miles off the Circars coast. At 2015 the wind, after having been variable Beaufort force 1, dropped to calm and after an interval of three minutes increased rapidly to gale force from NW. and at 2023 there were violent squalls accompanied by vivid forked lightning. The sky became overcast and rain followed at 2035. A quarter of an hour later the wind moderated, rain ceased and the sky began to clear, and at 2100 the wind backed to SW. and eventually to SE. where the principal wind had come from during the day."

4.7 WESTERN DISTURBANCES

During the six months from November to May, areas of cloudiness and precipitation move from west to east across northern India. Before the advent of satellites, such areas of disturbed weather were usually associated with surface lows and were therefore termed "western depressions." However, study of satellite photographs aided by an improved

upper-air network shows that it is not always possible to associate the surface of a low-level synoptic system with the area of disturbed weather. Western depressions, there fore, are now better referred to as "western disturbances."

According to "Weather in the Indian Ocean":

> *After entering India these depressions generally travel eastwards; they take 3 to 5 days to reach Bengal and sometimes extend into north Burma. Those disturbances which take a northerly course give rain in Kashmir and usually, after travelling for three days in Tibet, affect the weather in Assam. The time taken may sometimes be as long as five days but generally it is less. Those that take a more southerly track give rain in the central parts of northern India and in Orissa and squally weather off that coast and the Sundarbans.*
>
> *The paths of the depressions vary considerably from year to year and appear to be related to changes in the position of the Asiatic winter anticyclone.*
>
> *According to the most recent data the number of western depressions which have had some effect on the weather of northern and north-eastern India during the 10 years 1927-36 is no less than 460 or an average of 46 a year, varying from 35 in 1929 to 55 in 1934. Out of this total there were only 85 that affected the weather of north-east India and these were confined entirely to the six months from November to May and were most frequent in January and February. The distribution of the frequency of the depressions over the several months in north-east India is given in the following table, the depression has been allocated to the first month in which it was identified.*
>
> *North-east India. - Average Frequency of Western Depressions*
> *Period: 1927-36*

Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Year
2·4	2·2	1·4	1·4	0·2	0	0	0	0	0	0·1	0·8	8·5

It should be noted that the western disturbances referred to above could only have been identified from surface features since they occurred during the period 1927 through 1936.

A preliminary satellite study has been performed by Bhaskara Rao and Moray (1971) who, rather than identifying western disturbances from synoptic patterns, used satellite cloud pictures to identify areas of disturbed weather. They classified the various cloud forms into 5 main categories and then considered the synoptic patterns associated with each of the categories. The following types of cloud systems were catalogued:

(a) Systems with a vortex
(b) Latitudinal bands
(c) Meridional bands
(d) Overcast cloud masses (see Appendix C, Figure C-10)
(e) Broken amorphous cloud area (see Appendix C, Figure C-1)

The vortex type is typical of extra tropical cyclones of middle latitudes and the satellite-observed cloud patterns are associated with a surface low and frontal system. Occurrences of the vortex type would have been included in earlier studies. However, it was found that not all areas of disturbed weather, as detected by satellite, were associated with surface circulations; in many cases the areas of cloudiness appeared to be associated with upper air features only and these would not have been detected in the earlier studies.

Table 4-4 shows the monthly frequency of the different categories of cloud types occurring in 1968 and 1971. It should be noted that this does not give the frequency of western disturbances in each month, only the frequency of formation of a given cloud system.

It will be noted that disturbed weather areas occur with considerable frequency in the months considered.

It is known that western disturbances of the vortex type can cause a temporary intensification of the northeast monsoon over the Bay of Bengal, even when passing to the north of the head of the bay. This is due to southward-

moving cold air associated with the disturbance. The effect on the winter monsoon of disturbances not associated with a marked surface feature is not known and observations and comments would be welcome from forecasters in the field.

Table 4-4. Monthly frequency of different categories of cloud systems occurring in 1968 and 1971 (after Bhaskara Rao and Moray, 1971). (Area 40E to 90E and 15N to 60N)

	Type of Cloud System					Total
	V*	LB*	MB*	OM*	BA*	
1971						
Jan	0	0	3	4	2	9
Feb	0	2	6	5	4	17
Mar	1	4	1	2	4	12
Oct	2	0	1	2	3	8
Nov	1	1	4	1	4	11
Dec	0	3	1	3	7	14
1968						
Jan	0	0	1	7	6	14
Feb	1	3	2	3	7	16
Mar	0	0	0	4	8	12
Oct	2	0	0	2	4	8
Nov	2	0	2	1	8	13
Dec	2	0	0	6	9	17
Total	11	13	21	40	66	151

* V - Systems with a vortex, LB - Latitudinal bands, MB - Meridional bands, OM - Overcast cloud masses, BA - Broken amorphous clouded area.

5. THE MEAN ATMOSPHERIC CIRCULATION

5.1 INTRODUCTION

"The synoptic or climatological flow patterns of a monsoon regime are foreign to the typical American meteorologist whose tropical experience and training are usually confined to the persistent trade wind zones of the Western Hemisphere." (Sadler and Harris, 1970).

This section contains a description of the features which the forecaster/analyst will find on his charts when operating in the Bay of Bengal. The features presented refer to the undisturbed flow conditions; features such as those discussed in section 4 will be superimposed on the mean circulation. The material in this section is based almost entirely on "The Mean Tropospheric Circulation and Cloudiness over Southeast Asia and Neighboring Areas" by Sadler and Harris (1970), to whom due acknowledgement is made. Further details may be obtained by consulting the original publication.

5.2 FEATURES OF THE MEAN FLOW IN THE LOWER TROPOSPHERE

The complexity of the flow in the lower troposphere in the neighborhood of the Bay of Bengal may be appreciated by study of Figure 5-1, extracted from Sadler and Harris (1970). Consider first Figure 5-1A which shows a typical trade wind pattern between the sub-tropical ridges of the two hemispheres. The next degree of complexity is provided by allowing a thermal trough to develop in the northern hemisphere of sufficient intensity to cause tropical westerlies to the south of the trough (Figure 5-1B). When these anticlockwise circulations develop, it is also necessary for a clockwise-turning wind system to develop simultaneously between the westerlies associated with the trough and the easterly trades further to the south. This system is also

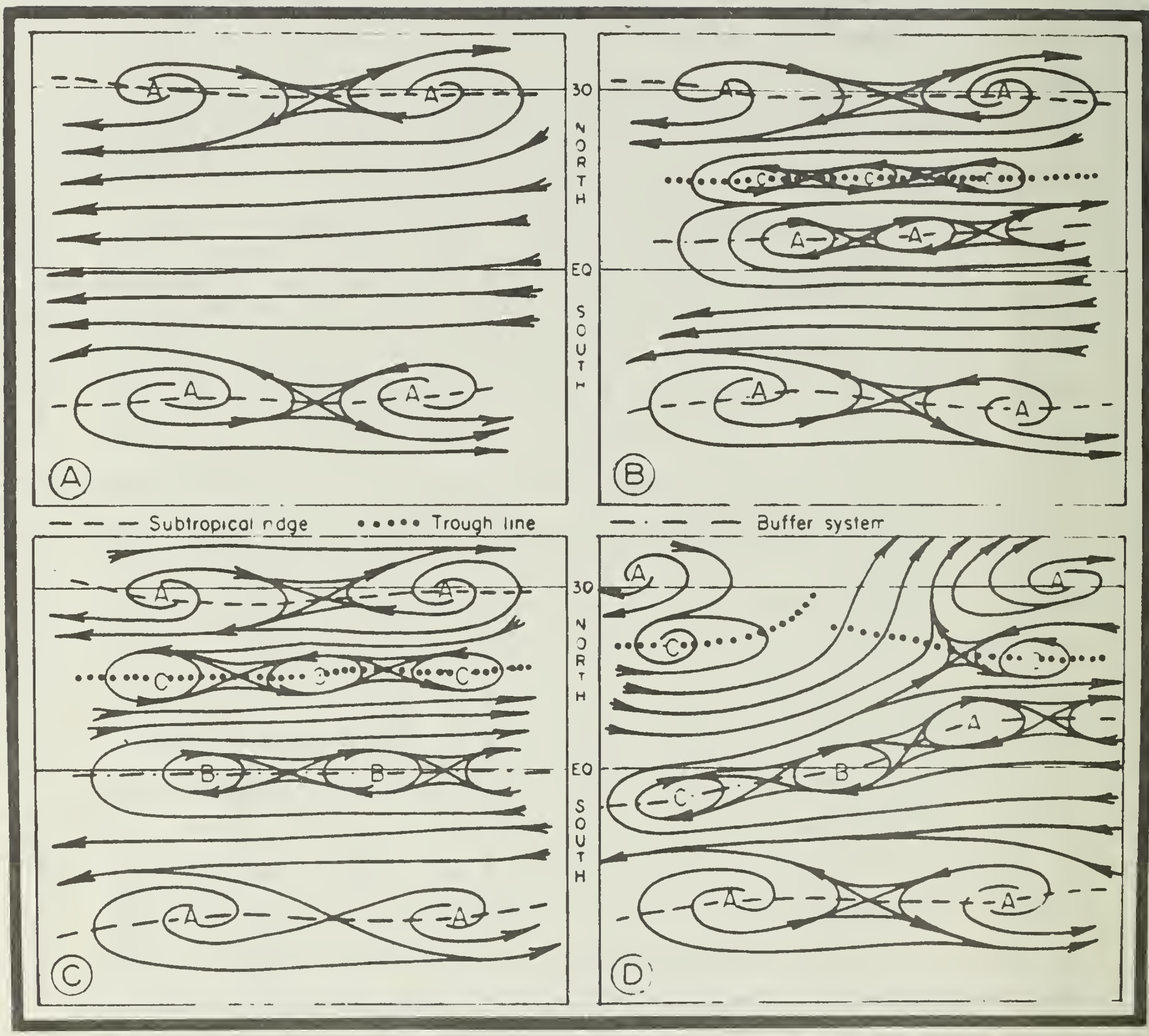


Figure 5-1. Schematic of low-level flow for an evolving monsoon circulation (from Sadler and Harris, 1970).

shown in Figure 5-1B, the centers of the circulations being marked "A." If the thermal trough continues to intensify, the tropical westerlies extend further south and the concomitant clockwise-turning circulations are also forced south. In Figure 5-1C these circulations are shown along the equator, the centers being marked "B." Figure 5-1D is a further modification showing the approximate mean conditions in the lower troposphere between India (on the left of the diagram) and the Philippines (on the right). The centers of the clockwise-turning circulations to the south of the equator are now labelled "C."

These clockwise-turning circulations are required by the development of the thermal trough. Some distance away from the equator, a clockwise-turning circulation in the northern hemisphere is anticyclonic and is associated with high pressure and low-level divergence. In the southern hemisphere such a circulation is cyclonic and is associated with low pressure and low-level convergence. It is usual to label such circulations "A" or "C" respectively and this procedure has been followed in Figure 5-1. However, in low latitudes, due to the fact that the Coriolis force decreases to zero as the equator is approached, such associations are no longer valid. Thus, although the circulations are labelled "A" or "C" one cannot necessarily associate divergence and convergence with the circulations; this is indicated by using a "closed streamline." In higher latitudes streamlines are normally drawn to show divergence or convergence from or into an anticyclonic or cyclonic center. In the immediate vicinity of the equator a clockwise-turning circulation cannot be designated "A" or "C" and the centers are marked "B." From Figure 5-1D it can be seen that the clockwise-turning circulations act as a "buffer" between the circulation patterns of the two hemispheres; they are

therefore termed the buffer system or "buffer zone" after Sadler and Harris (1970).

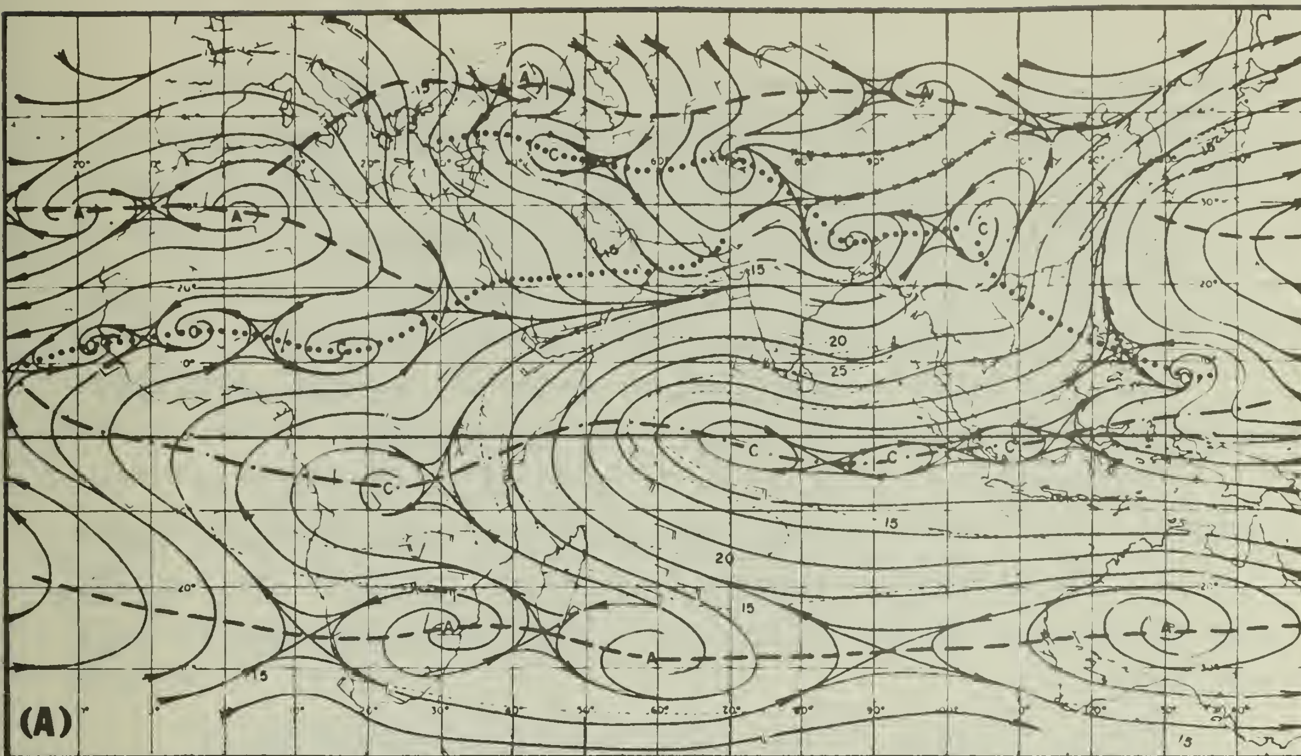
Climatological charts of the mean flow in the lower troposphere for selected months are given in Appendix B.

5.3 THE TOTAL MONSOON SYSTEM IN OPPOSING SEASONS

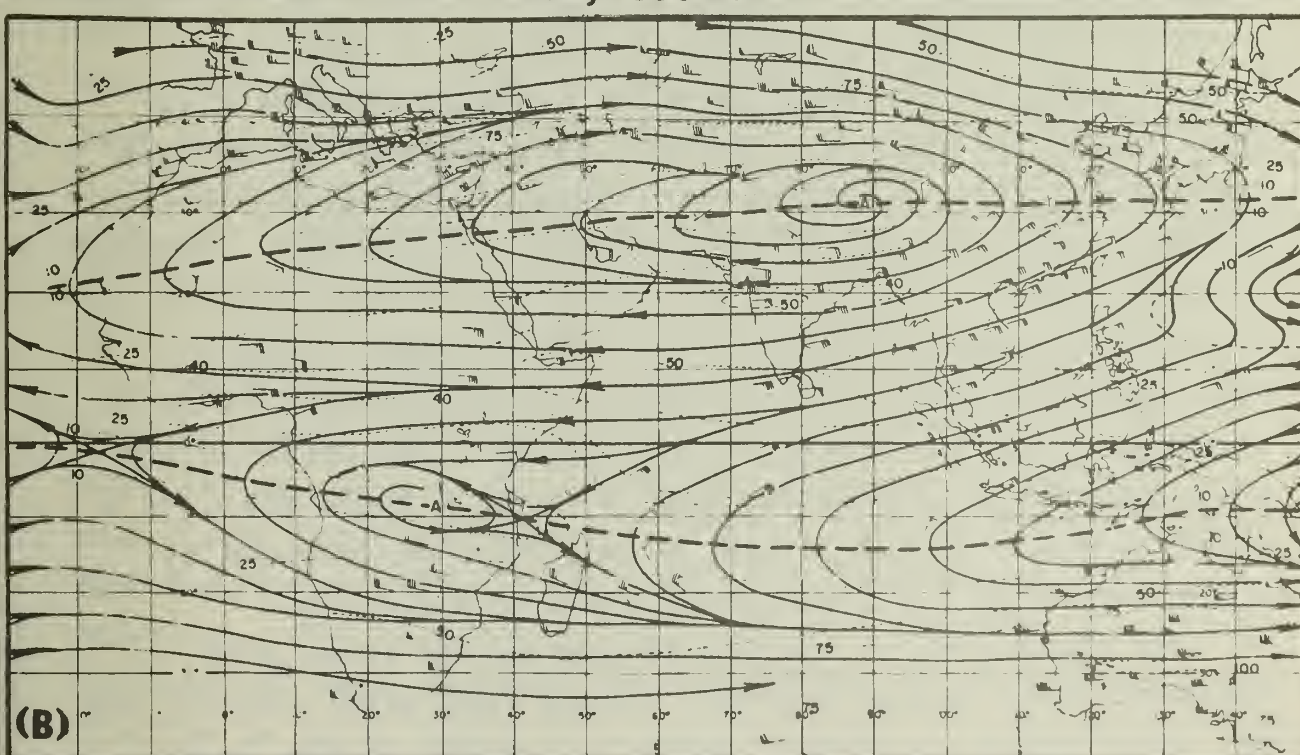
Sadler and Harris (1970) have provided an excellent description of the total monsoon system in opposing seasons by considering the 850-mb and 200-mb levels for July and January. The following paragraphs are relevant to the area under discussion and are based on their description; for further details the original publication may be consulted.

5.3.1 July

850 mb (Figure 5-2A). In July, the low-level clockwise-turning wind system near the equator (noted as dot-dash line) between the basic flows of the monsoon westerlies of the summer hemisphere and the trade wind regime of the winter hemisphere extends from the western Pacific to the eastern Atlantic. The portion of this system, lying in the longitudes of India and the Bay of Bengal and south of the equator, is the southern hemisphere near-equatorial trough. However, there are occasions when the system migrates north of the equator. When this occurs the clockwise-turning circulation is anticyclonic in nature and, in the Indian region, it has been referred to as the sub-tropical ridge. Confusion has arisen due to the fact that the system is often not recognized nor treated as continuous. According to Sadler and Harris, "the system is continuous in space and time and daily responds in position to the fluctuations in the intensity and configuration of the two basic currents. The system is not anchored orographically, can move back and forth across the equator, and can have a synoptic-scale cellular structure with the cyclonic or anticyclonic rotational sense being determined by the position with respect to the



July 850 mb



July 200 mb

Figure 5-2. Mean resultant winds. Solid lines are streamlines Dashed lines are isotachs labled in knots (from Sadler and Harris, 1970).

equator (i.e., a ridge or anticyclone when north of the equator, and a trough or cyclone when south of the equator)." However, as discussed in paragraph 5.2, the association of divergence or convergence with these circulations is not valid in the immediate vicinity of the equator. Sadler and Harris refer to the system as the "buffer system."

The low level trough system north of the Bay of Bengal, noted by a dotted line, is the monsoon trough.

The tropical or monsoon westerlies are deeper, of greater latitudinal extent, and stronger over southern India and the Bay of Bengal than in any other region. This feature may be related to the influence of the Himalayan Massif (see paragraph 3.3).

200 mb (Figure 5-2B). The Himalayan Massif helps produce and anchor an intense anticyclone near 90E and just north of 30N. The eastward extension of the subtropical ridge from this cell remains above 30N over eastern Asia and the western Pacific. Between this intense anticyclone and the subtropical ridge of the Southern Hemisphere exists the most extensive and strongest upper tropospheric easterly wind belt within the tropics. There is a strong cross-equatorial component of flow into the Southern Hemisphere over the broad longitudinal expanse from 50E to 150E, being strongest over the central Indian Ocean. The observations also indicate that over the central Indian Ocean there is a strong poleward flow of some 20 kt across the subtropical ridge axis into the Southern Hemisphere westerlies.

An inspection of the 850 mb and 200 mb flows over Southeast Asia reveal a broad, strong (and moist--Harris and Ho, 1969) speed-convergent westerly current in the lower levels overlain by a broad, strong, speed-divergent easterly flow aloft--the textbook model of a weather factory.

5.3.2 January

850 mb (Figure 5-3A). The Southern Hemisphere summer monsoon trough extends from western Africa to beyond 180°. At 850 mb it is oriented essentially east-west, lying between 10S and 20S, and is nearest the equator in the central Indian Ocean. Vortices within the trough act as seedlings for the development of tropical storms in the South Indian Ocean and in the southwest Pacific Ocean. The monsoon westerlies equatorward of the trough, although more extensive longitudinally than the Northern Hemisphere summer monsoon westerlies, are much weaker and narrower. The average strength and width are approximately 10 kt and 15 degrees of latitude, respectively.

The counterclockwise "buffer system" between these westerlies and the tropical easterlies of the winter hemisphere is a trough system when north of the equator and a ridge system when south of the equator. Climatically it lies just north of the equator between 60E and 160E and occasionally vortices within the trough (particularly if it migrates north of 5N) develop into depressions and tropical storms in the western North Pacific, southern South China Sea, southern Bay of Bengal, and southern Arabian Sea.

200 mb (Figure 5-3B). The Southern Hemisphere subtropical ridge is located near 14S over Australia and 18S over Africa, only a small southward shift from its July mid-winter position; the subtropical ridge of the Northern Hemisphere has moved 20 degrees equatorward of its July position. The easterlies are therefore confined to a narrow latitudinal belt and have maximum speeds of less than 30 kt. Similar to July, there is a cross-equatorial component of flow into the winter hemisphere and a poleward flow across the winter ridge axis. This poleward flow is a maximum from the western Pacific through India, or again just upstream from the winter jet stream maximum.

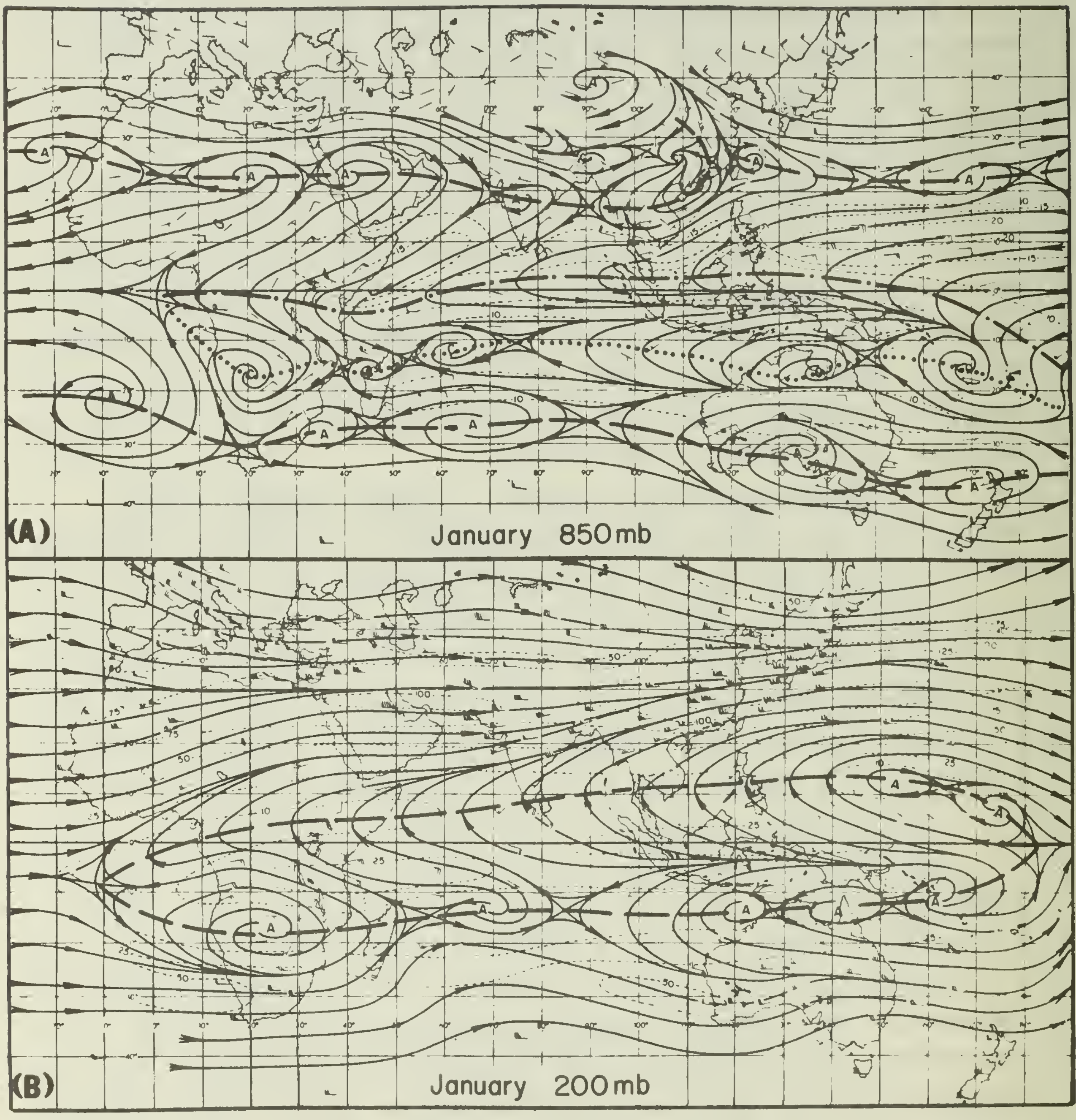


Figure 5-3. Mean resultant winds. Solid lines are streamlines. Dashed lines are isotachs labled in knots (from Sadler and Harris, 1970).

6. THE MARCH OF THE SEASONS IN THE BAY OF BENGAL

6.1 INTRODUCTION

In the Bay of Bengal there are four distinct seasons: the winter monsoon, the spring transition period, the summer monsoon, and the fall transition period. Approximate timings for these seasons are given in paragraph 3.5. The actual timing of the seasons varies from year to year and the forecaster in the Bay of Bengal must take this into consideration. For example, in late September, a forecast should not be based on the normal characteristics of summer monsoon weather if, from the charts, it is evident that the monsoon trough has weakened and a near-equatorial trough lies across the central part of the bay. Under these circumstances, cyclonic storm formation is much more likely than in the average September.

Most of the information pertinent to seasonal changes in the Bay of Bengal is contained in other sections. The object of this section is to link the information presented elsewhere in this Handbook into a time-ordered sequence. To avoid repetition, frequent references will be made to these other sections.

Tables 6-1 and 6-2 from Ramage (private communication) give climatic tables for areas "A" and "B." These areas are shown on Figure B-2(a), Appendix B. It is instructive to consult these tables while studying the description of the various seasons.

6.2 THE WINTER MONSOON - DECEMBER THROUGH MARCH

Northeast monsoon conditions prevail over the whole area with the northern near-equatorial trough lying near 5N (Figure 4-2). The principal trough at this time of year is, of course, the near equatorial trough of the southern hemisphere. (See Figures B-3(a) and B-3(b)).

Table 6-1. Climatic table for ocean area A centered at latitude 14°30'N Longitude 87°30'E

Mo	Mean Press (mb)	Mean Temp (°C)	Mean Vapor Press (mb)	Mean Sea Sfc Temp (°C)	% Freq. of Pre-cip	% Freq. of Light ning	% Freq. of Gale	Mean Clou di ness (%)	Most Freq Wind Dir	Mean Wind Vel (m sec^{-1})	Net Heat Bal. at Sea Sfc (cal cm^{-2} day^{-1})
J	1013.6	25.3	22.8	26.1	3	2	0	25	NE	5.7	-26
F	1012.7	25.4	26.5	26.1	0	2	0	15	NE	3.0	283
M	1011.5	26.6	27.8	27.2	0	2	0	12	NE	3.0	323
A	1008.9	28.3	32.6	28.9	2	7	0	20	S	3.5	310
M	1006.3	29.3	33.5	29.4	6	10	0	38	SW	5.6	221
J	1003.6	28.9	33.5	28.9	10	12	2	74	SW	8.9	-25
J	1003.9	28.2	33.2	28.3	13	9	3	78	SW	9.3	50
A	1004.3	27.8	33.2	27.8	13	8	1	60	SW	8.3	116
S	1006.6	27.7	31.7	28.3	12	9	0	60	SW	6.6	83
O	1009.0	27.7	31.7	28.3	12	9	0	46	SW	4.7	160
N	1010.0	27.2	28.1	27.8	10	6	0	48	NE	6.0	-53
D	1012.7	25.8	25.3	26.7	7	3	3	49	NE	6.8	-186
Y	1008.6	27.4	30.0	27.8	7.3	6.6	0.8	44	SW	6.0	101

Table 6-2. Climatic table for ocean area B centered at latitude 6°N Longitude 88°30'E

Mo	Mean Press (mb)	Mean Temp (°C)	Mean Vapor Press (mb)	Mean Sea Sfc Temp (°C)	% Freq. of Pre-cip	% Freq. of Light ning	% Freq. of Gale	Mean Clou di ness (%)	Most Freq Wind Dir	Mean Wind Vel (m sec^{-1})	Net Heat Bal. at Sea sfc (cal cm^{-2} day-1)
J	1011.0	27.2	29.1	27.2	14	8	0	45	NE	4.9	175
F	1010.6	27.4	29.3	27.8	8	10	0	41	NE	3.0	228
M	1010.3	27.7	30.1	28.3	10	11	0	45	NE	3.0	236
A	1009.2	28.3	31.3	28.9	13	15	0	49	SW	2.9	207
M	1008.4	28.2	31.7	28.3	15	15	0	59	SW	6.3	98
J	1008.2	28.1	31.6	28.3	13	6	0	63	SW	7.2	48
J	1008.5	27.8	31.0	27.8	9	4	0	63	SW	7.6	42
A	1009.2	27.6	30.7	27.8	12	4	0	63	SW	7.3	-18
S	1009.6	27.4	30.5	27.8	13	4	0	63	SW	6.8	-2
O	1010.1	27.2	29.2	27.8	18	5	0	62	SW	4.8	76
N	1010.3	27.1	29.2	27.8	17	4	0	63	SW	4.0	85
D	1010.6	27.2	29.4	27.8	16	7	0	52	NE	3.9	109
Y	1009.7	27.6	30.2	28.0	132	7.8	0	56	SW	5.1	104

Surface winds (Figures B-2(b) and B-3(a)) are from the north to east and are generally 21 kt or less. Other data show that they rarely exceed 27 kt except in December or in association with cyclonic storms (Figure 4-10). Paragraph 5.3.2 discusses low level and upper level wind flow features, and Figure B-3 (Appendix B) gives mean streamline charts at various levels in January.

The development of cyclonic storms in the Bay of Bengal is rare in winter and is discussed in section 4, in particular paragraph 4.5.5. In the far south of the bay, however, when the near-equatorial trough of the northern hemisphere moves to the north of its mean position, cyclonic disturbances may occasionally develop (see Figure 4-10). According to Sadler and Harris (1970), these cyclonic disturbances may provide a deep moisture source which is transported across the Bay of Bengal, Burma, and Thailand by the upper southwesterly winds in the form of thick cirrus and altostratus. A forecaster, seeing such clouds, should suspect cyclonic activity upstream of the upper flow, and that the northern near-equatorial trough has moved to the north of its mean position.

In December the surface pressure over northern India reaches its maximum value (Figure B-1, Appendix B). At the same time, the summer monsoon of the southern hemisphere intensifies and the heat low deepens over Australia and Africa. For these reasons the northeast monsoon is most intense during December and occasionally reaches gale force. This can be seen in Figure 4-14(b) where there is a secondary maximum of gales during December. It is clear from a comparison of Figures 4-10, 4-14, and 4-15, that most of these gales are due to intensification of the winter monsoon rather than associated with cyclonic storms.

In general, surges in the northeast monsoon are much weaker than those experienced in the South China Sea but, nevertheless, they do occur. Apart from surges associated with temporary intensifications of the southern hemisphere near-equatorial trough, the so-called "western disturbances" (see paragraph 4.7) may also lead to increases in winter monsoon wind strength. Western disturbances may be detected on satellite photographs (Figures C-1 and C-10, Appendix C) and tracked but, at this time, it is not known if the forecaster will have much success in forecasting surges in the northeast monsoon.

In March the spring transition period is approaching and, on the average, the near-equatorial trough starts to migrate northward. The southern hemisphere monsoon decreases in intensity at high and low levels. Due to the increasing temperature of the land around and to the north of the Bay of Bengal and the consequent change in the general distribution of pressure, the northeast monsoon winds become less steady. In fact, north of about 15N, the winds are frequently southerly or southwesterly; further south, to about 5N, the northeasterly winds of the winter monsoon still prevail. Off the coast of India the winds become more easterly south of 15N. The mean wind speed in March is generally 4 to 10 kts although occasionally reaching 28 to 33 kts. Squalls which may cause a high sea are sometimes experienced in the northern part of the bay, often being associated with western depressions. Cloudiness over the area increases as the northeast monsoon weakens.

In general, during the winter months, scattered cloudiness affects the northern part of the bay, the mean cloud cover increasing towards the south (Figures B-7(a), and C-1).

Winter is dry except on the Coromandel Coast and the Gulf of Mannar in December when, on the average, as much as 6 to 8 inches of rain falls. The percentage of frequency of observations reporting precipitation (all types) is given in Figure B-8 for all months.

Sea surface temperatures in the south of the bay are about 84F throughout the year (see Figure B-9). However, at the head of the bay, near the Mouths of the Ganges, large seasonal variations of about 20F occur. In December the sea surface temperature at the head of the bay is about 66F (Figure B-9(1), having fallen by 10F from the mean value for November. This temperature distribution persists during January. In February temperatures at the head of the bay rise to about 76F, increasing to 82F in March.

6.3 THE SPRING TRANSITION SEASON - APRIL THROUGH MAY

During the winter, monsoon pressure is high over northern India, decreasing to the south across the Bay of Bengal. The mean pressure reaches a secondary minimum to the north of the equator, the primary minimum lying in the southern hemisphere. These minima are the near-equatorial troughs (see Figure 4-2).

As winter progresses into spring, the amount of insolation received by the northern hemisphere increases and the near-equatorial troughs "follow the sun" northward. As this occurs the northern trough deepens and the southern trough weakens. If the earth possessed uniform absorption and emission characteristics of radiation, a more-or-less steady northward movement of the troughs would occur. Due to the non-uniformity of the earth with respect to radiation, however, a thermal trough begins to develop over northern India at the same time as the near-equatorial troughs begin their northward movement. This reduces the north-south pressure gradient and winds over the bay become variable.

Eventually the thermal trough intensifies to such an extent that the pressure gradient over the bay is reversed, the northern equatorial trough dissipates or perhaps merges with the thermal trough over northern India to become the monsoon trough, and the southwest monsoon of summer sets in.

The period during which the pressure gradient is reversing corresponds to the spring transition season; compare Figures B-1(a) (the northeast monsoon), B-1(b) (spring reversal of pressure gradient), and B-1(c) (summer monsoon) in Appendix B.

This sequence of events causes the northern near-equatorial trough to move discontinuously across the bay from its mean winter position to its mean summer position (see Figure 4-2). During the transition season the trough may or may not be detectable over the bay and the forecaster should not expect continuity from chart to chart. See also paragraph 4.2.3.

The presence of the intensifying thermal trough over northern India means that southwesterly winds may be experienced in the northern part of the bay before they are observed further south. This can be seen by comparing Figures B-2(b) and B-2(c) in Appendix B which show that winds become lighter and more variable and that southwest winds become more persistent in the northwest part of the bay before they do further south. Near the coast, land and sea breezes prevail. The wind roses for May (Figure B-2(d)) show that, by this month, southwest winds affect most of the bay much of the time. The 850-mb streamline charts given in Appendix B should also be compared.

Figures 4-14 and 4-15 show that in "area A" there is a marked change in mean wind direction between March and April, and by May the winds are almost exclusively south to southwest. Gales are unlikely, but winds $\geq$22 kts increase rapidly in frequency in late April or early May.

Over the Bay of Bengal the frequency of occurrence of tropical cyclones increases from March onward (Figure 4-10A). For reasons given in section 4 (in particular, paragraph 4.5.5) there is a secondary maximum in cyclonic storm development in May (Figure 4-10D). See also Appendix A. An example of a cyclonic storm in May is given in Figure C-3.

Mean cloudiness increases during the period (compare Figures B-7(a) and B-7(b) in Appendix B) especially in the south. Showery, squally weather may be experienced at any time, increasing in frequency during May (see Figure C-2). Heavy rain and thunderstorms frequently occur during the squalls. "Nor'westers" may also be experienced within about 100 miles of the coast in the northern part of the bay, especially in association with western disturbances (see paragraphs 4.6 and 4.7). The percentage frequency of observations reporting precipitation increases (see Figure B-8).

Due to the decrease in wind strength combined with the relatively low cloud amounts, this is the hottest time of the year over the bay. Sea surface temperatures reach a maximum in May and over the sea it is hot, sultry, and humid.

6.4 THE SUMMER MONSOON - JUNE THROUGH SEPTEMBER

As spring progresses into summer, the monsoon trough over northern India becomes more intense (Figures 4-2 and B-1(c)). As it increases in intensity the southwesterly winds become stronger and more persistent (Figures B-2(e) and 4-14).

The development of persistent southwesterly winds marks the end of the spring transition and the start of summer. At first, however, the southwesterly winds are not persistent, occurring in periods separated by variable or even north-easterly winds. The initial occurrence of southwesterly winds does not normally correspond to the onset of the rainy

season (see paragraph 3.1). Figure 6-1 shows the average dates of the onset of the summer rains.

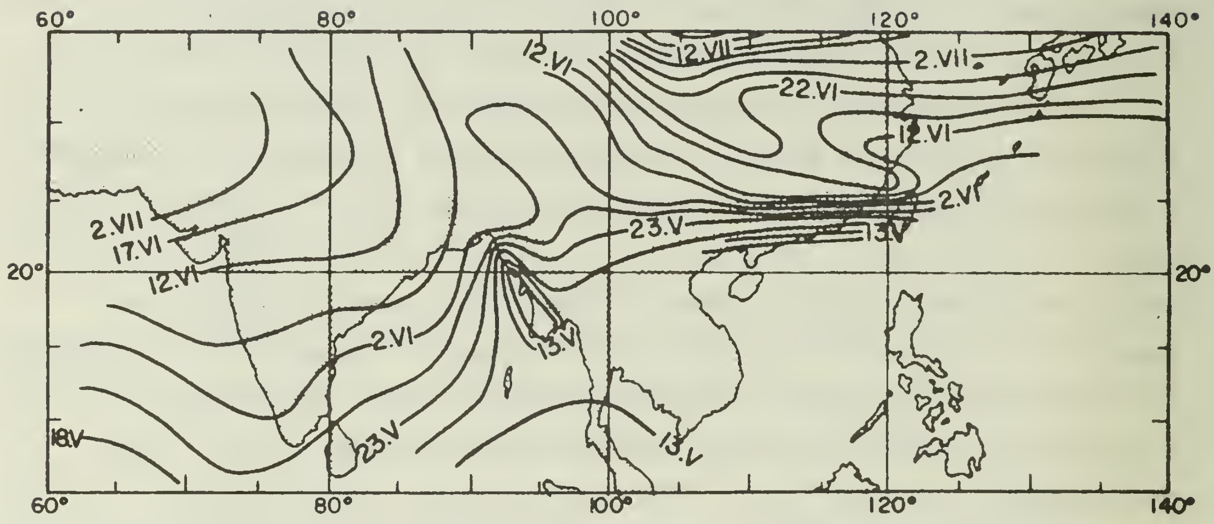


Figure 6-1. Average onset dates of the rainy season (from Ramage, 1971). Note: Roman numerals refer to months.

Figure B-8 shows the percentage frequency of observations reporting precipitation. Note that the highest frequencies occur in the northeastern part of the bay due to the air mass picking up moisture as it crosses the bay. Cloud amounts are very high during the season (Figures B-7(c) and C-6), July being the cloudiest month.

The most remarkable feature during this season is the occurrence of monsoon depressions; these are discussed in paragraphs 4.3 and 4.5. Figures C-4 and C-5 (Appendix C) show examples of monsoon depressions. They develop in the northern part of the bay in association with the movement of the monsoon trough southward to lie across the head of the bay. According to Atkinson (1971), "After formation, these depressions, which seldom reach tropical storm intensity, move inland along the trough to the northwest." The frequency

of cyclonic disturbances increases throughout the period but it is not until September that a significant percentage achieve cyclonic storm intensity.

Any development of mid-tropospheric cyclones would be expected to occur during the southwest monsoon. Ramage (private communication) believes that they are most likely at the beginning or end of the summer rather than in the middle. Mid-tropospheric cyclones are discussed in paragraph 4.4. The occurrence of such phenomena appears to be rare and operational forecasters are requested to report such systems to the Environmental Prediction Research Facility.

The frequency distribution of cyclonic disturbances in the bay is shown in Figure 4-10. Paragraph 4.5.5 discusses cyclonic storm development and explains the distribution shown in Figure 4-10. Appendix A gives tracks of cyclonic disturbances and contains comments on track characteristics.

Figure 4-15 gives, for area "A", the monthly distribution of strong and gale force winds. This should be compared with Figure 4-10. Note that in area "A" strong winds ($\geq$22 kts) increase rapidly to a peak in July at which time the percentage frequency of occurrence is about 34%. The frequency of strong winds then decreases but the percentage of winds reaching gale force increases to a maximum in September. These characteristics are due, in part, to the location of area "A" in the Bay of Bengal and should not be considered as typical of the bay during the summer months. This is made obvious from a study of cyclonic storm tracks occurring during the summer months (Appendix A). See also paragraph 4.6.

Figure B-2(e), Appendix B, shows strong southwesterly winds, at times reaching gale force, affect the Bay of Bengal during the summer monsoon. Once the monsoon is established these winds continue to blow until the onset of the fall transition season.

The mean atmospheric circulation for July is compared with that of January in section 5. Figure B-5 gives mean streamline charts for upper levels in July.

Severe squalls and heavy rain occur over the whole area during the summer monsoon. It is hot (Figure B-9), wet (Figure B-8), cloudy (Figure B-7), and windy. However, due to increased cloudiness and evaporation, air and sea temperatures are slightly lower than during the spring transition period.

6.5 THE FALL TRANSITION SEASON - OCTOBER THROUGH NOVEMBER

During the summer monsoon, pressure is low over northern India, increasing to the south across the Bay of Bengal (Figure B-1(c), Appendix B).

As summer progresses into fall, the amount of insolation received by the northern hemisphere begins to decrease and the monsoon trough over northern India weakens. This causes the south-north pressure gradient to decrease and hence the southwesterly winds become less strong. As the sun moves south and the thermal trough weakens, the northern near-equatorial trough becomes more discernable and moves across the bay, following the sun (see Figure 4-2). Winds over the northern parts of the bay to the north of the trough become first variable and then northeasterly; this progression can be seen for area "A" in Figure 4-14.

As the southwest monsoon weakens over the northern part of the bay, fine weather frequently occurs for considerable periods with land and sea breezes prevailing. This decrease in cloudiness in the north does not apply to the more southerly parts of the bay for there, as a consequence of the passage of the near-equatorial trough, some of the heaviest rains of the year occur on the east coast of India to the south of Orissa (Figure C-7). Appendix B shows precipitation frequencies (Figure B-8) and cloud amounts (Figure B-7).

At this time of the year the danger of severe cyclonic storms occurring is greater than at any other time (see Figure 4-10). Tropical cyclones are discussed in detail in section 4. Appendix A give storm tracks and comments on the characteristics of these tracks. Satellite photographs of a cyclonic storm are shown in Figures C-8 and C-9.

Surface wind roses for October are shown in Figure B-2(f). However, these should be treated with reservation when considering the frequencies of strong or gale force winds since these are normally associated with intense cyclonic circulations which ships endeavor to avoid. The data is thus biased toward lighter winds.

Streamline charts for the fall transition season are shown in Appendix B.

In October and November, thunderstorms are fairly frequent on the southern coast of India. In November, as the near-equatorial trough continues to move south, the weather over the sea in the northern part of the bay remains generally fine except when disturbed by a cyclonic storm. In the south and in equatorial regions squally, showery weather is experienced. By December the northeast monsoon of winter has become established over the whole area and the conditions described in paragraph 6.2 once again apply.

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APPENDIXES

APPENDIX A

TRACKS OF STORMS AND DEPRESSIONS IN THE BAY OF BENGAL AND THE ARABIAN SEA, 1877-1960

1. INTRODUCTION

The charts presented in this appendix were extracted from Tracks of Storms and Depressions in the Bay of Bengal and the Arabian Sea, 1877 - 1960, originally published by the India Meteorological Department (1964). The analytical descriptions were provided by the same source. Note that the charts presented show the tracks of only those cyclonic disturbances which, at some time in their life cycle, reached cyclonic storm intensity.

2. DESCRIPTIVE ANALYSIS

Figures A-1, A-2, and A-3: January, February, and March. Tropical storms do not occur in the Arabian Sea in these months. In the Bay of Bengal they are few and far between. They originate between 5N and 8N, move in a westerly or northwesterly direction and strike the south Coromandel coast or the east coast of Ceylon. They have a tendency to weaken and dissipate over the sea area in the course of their movement.

Figure A-4: April. Most of the bay storms in this month originate between 8N and 13N and east of 85E. Their direction of movement is initially toward the northwest or north; later they recurve toward the northeast and strike the Arakan coast of Burma. The general direction of movement of storms in the Arabian Sea is similar to that of bay storms. After recurving, they move toward the Kathiawar-Sind-Makran coast.

Figure A-5: May. There is an appreciable increase in the frequency of storms from April to May. Most of the bay storms originate between 10N and 15N, move initially in a northwesterly or northerly direction and then recurve toward the northeast. The whole of the east coast of India, the coastal areas of Bangladesh and the Arakan coast of Burma are liable to incidence of storms in this month. A number of them are of severe intensity. In the Arabian Sea, storms in this month move northwest toward the coast of Arabia. A few move in a northerly direction toward the Konkan-Kathiawar coast.

Figure A-6: June. There is a striking change from May to June. Almost all the Bay of Bengal storms in this month originate between 16N and 21N and west of 92E. The great majority of them move toward the northwest and weaken into depressions after crossing the coast. In the course of further movement, the tracks curve toward the north or north-northeast. In the Arabian Sea, most of the storms in this month are confined to the area north of 15N and east of 65E.

Figure A-7: July. Bay storms in this month form north of 18N and west of 90E and move generally in a west-north-westerly direction. The tracks of these disturbances are largely confined to the latitudinal belt from 20N to 25N. Severe cyclonic storms are few in this month. There is an abrupt drop in the frequency of storms over the Arabian Sea to almost nil in July.

Figure A-8: August. The main features of the storm tracks in this month are similar to those for July except that the tracks in their initial stages have a more northwesterly course and show a larger latitudinal scatter. West of 80E the tracks tend to curve toward the north. The Arabian Sea is practically free from storms in this month.

Figure A-9: September. Most of the bay storms originate in the area north of 15N and west of 90E. They move initially in a west to northwesterly direction and later recurve toward the north-northeast. The frequency of storms in the Arabian Sea is low in this month.

Figure A-10: October. In this month, storms in the Bay of Bengal originate between 8N and 14N. They move initially in a northwesterly direction. Most of them later recurve and move toward the northeast. The north Coromandel and Circars coasts and the coastal belt of Bangladesh are particularly vulnerable to the incidence of storms in this month. Most of the storms that strike the coast south of 15N enter the Arabian Sea and re-intensify. In the Arabian Sea, the direction of movement of storms is generally westerly. However, east of 70E some of the storms move north-north-westwards and later recurve northeast to strike the north Konkan-Kathiawar coast.

Figure A-11: November. The source region of the majority of storms in this month is between 8N and 13N. Those which move in a west-northwesterly direction strike the Coromandel coast and emerge into the Arabian Sea where they re-intensify. Bay storms which form in more northerly latitudes move north-west and later recurve toward the northeast. In the Arabian

Sea, the initial movement is northwesterly. Storms which go north of 15N recurve toward the northeast and strike the north Konkan-south Kathiawar coast.

Figure A-12: December. There is an appreciable decrease in the frequency of storms from November to December. Most of the storms originate over the Bay of Bengal between 5N and 10N. Those which originate over the southwest bay move initially in a northwesterly direction and strike the south Coromandel coast or the northeast coast of Ceylon. A few of these enter the Arabian Sea. However, they do not intensify but dissipate. Storms which originate in the southeast bay generally move in a north-northwesterly direction and later recurve toward northeast. During their northeasterly course they show a tendency to weaken and dissipate. Storms in the Arabian Sea are very few in December and almost all of them are of bay origin.

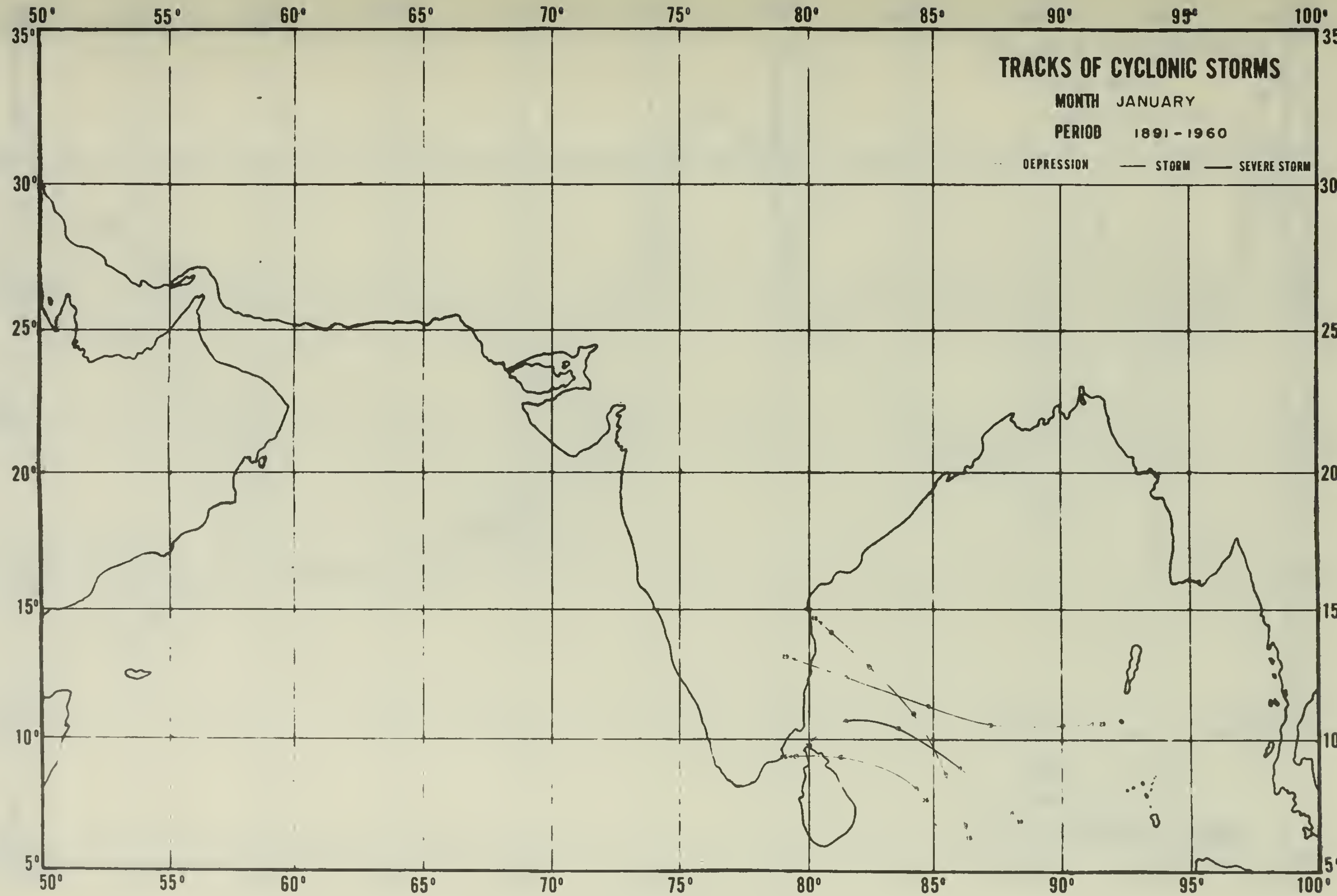
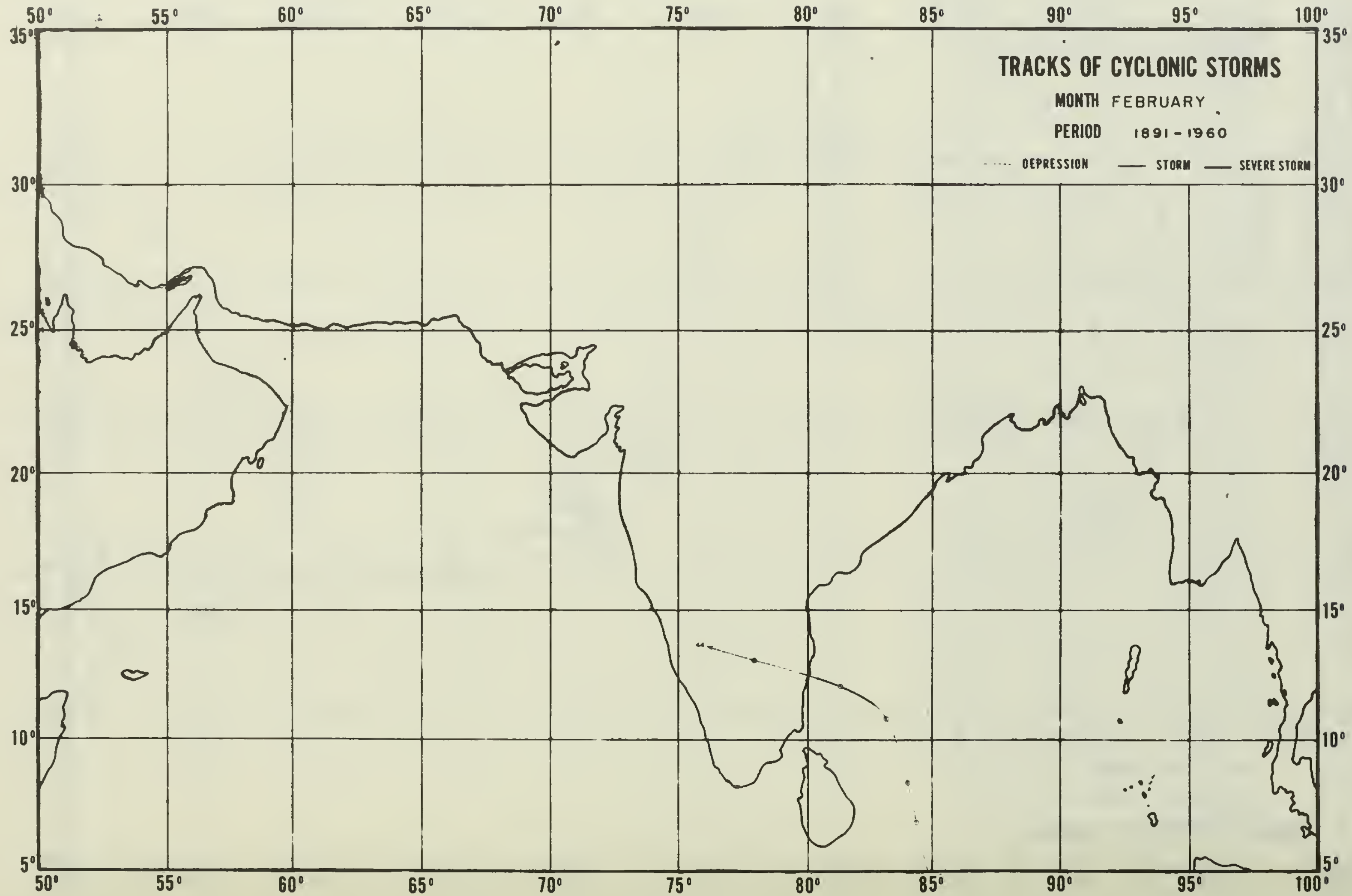

TRACKS OF CYCLONIC STORMS
MONTH JANUARY
PERIOD 1891 - 1960
DEPRESSION
STORM
SEVERE STORM
50°
55°
60°
65°
70°
75°
80°
85°
90°
95°
100°
35°
30°
25°
20°
15°
10°
5°

Figure A-1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MONTH FEBRUARY
PERIOD 1891-1960
DEPRESSION
STORM
SEVERE STORM
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55°
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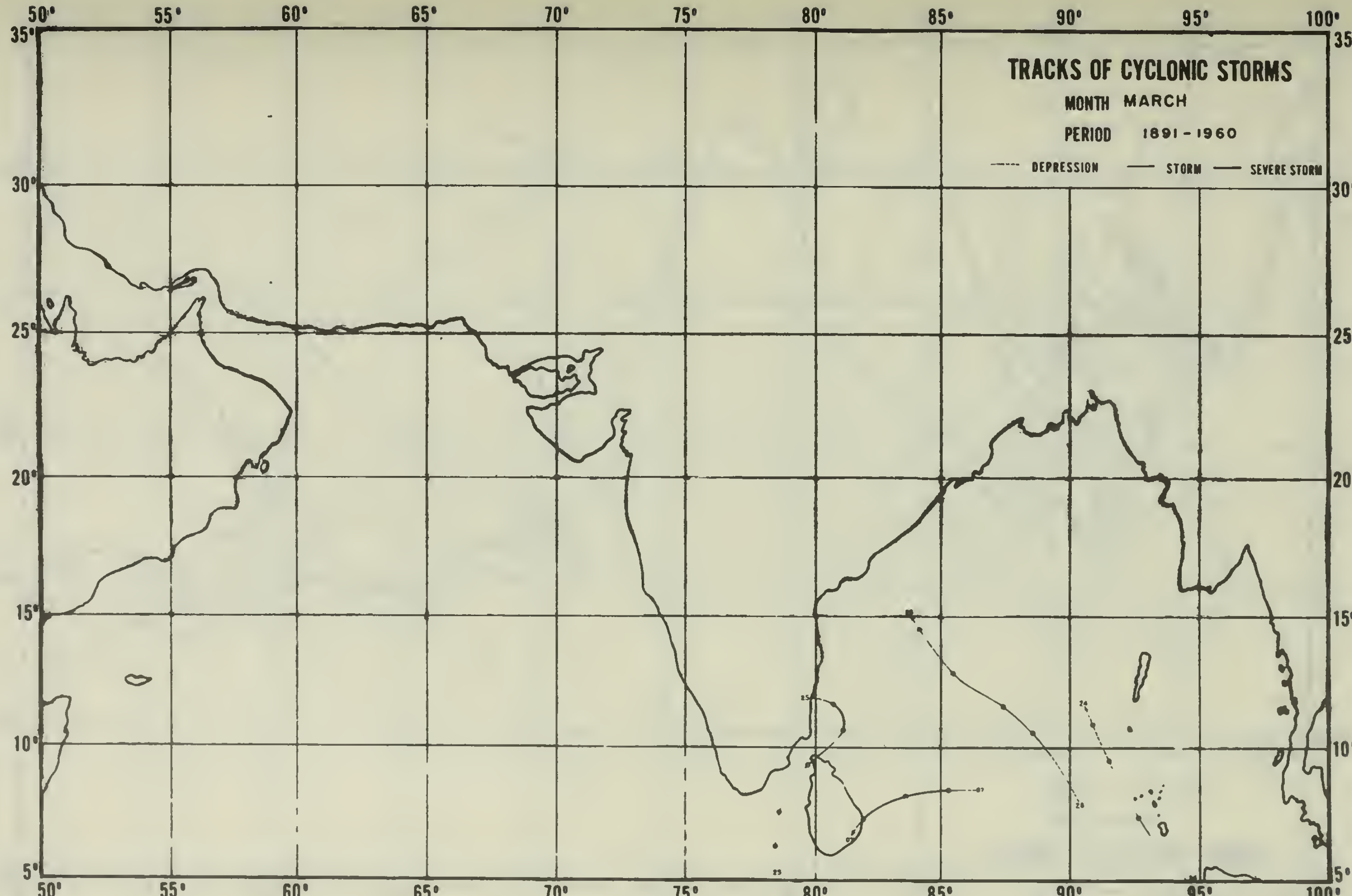
Figure A-2


TRACKS OF CYCLONIC STORMS
MONTH MARCH
PERIOD 1891-1960
DEPRESSION
STORM
SEVERE STORM
50°
55°
60°
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70°
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90°
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100°
35°
30°
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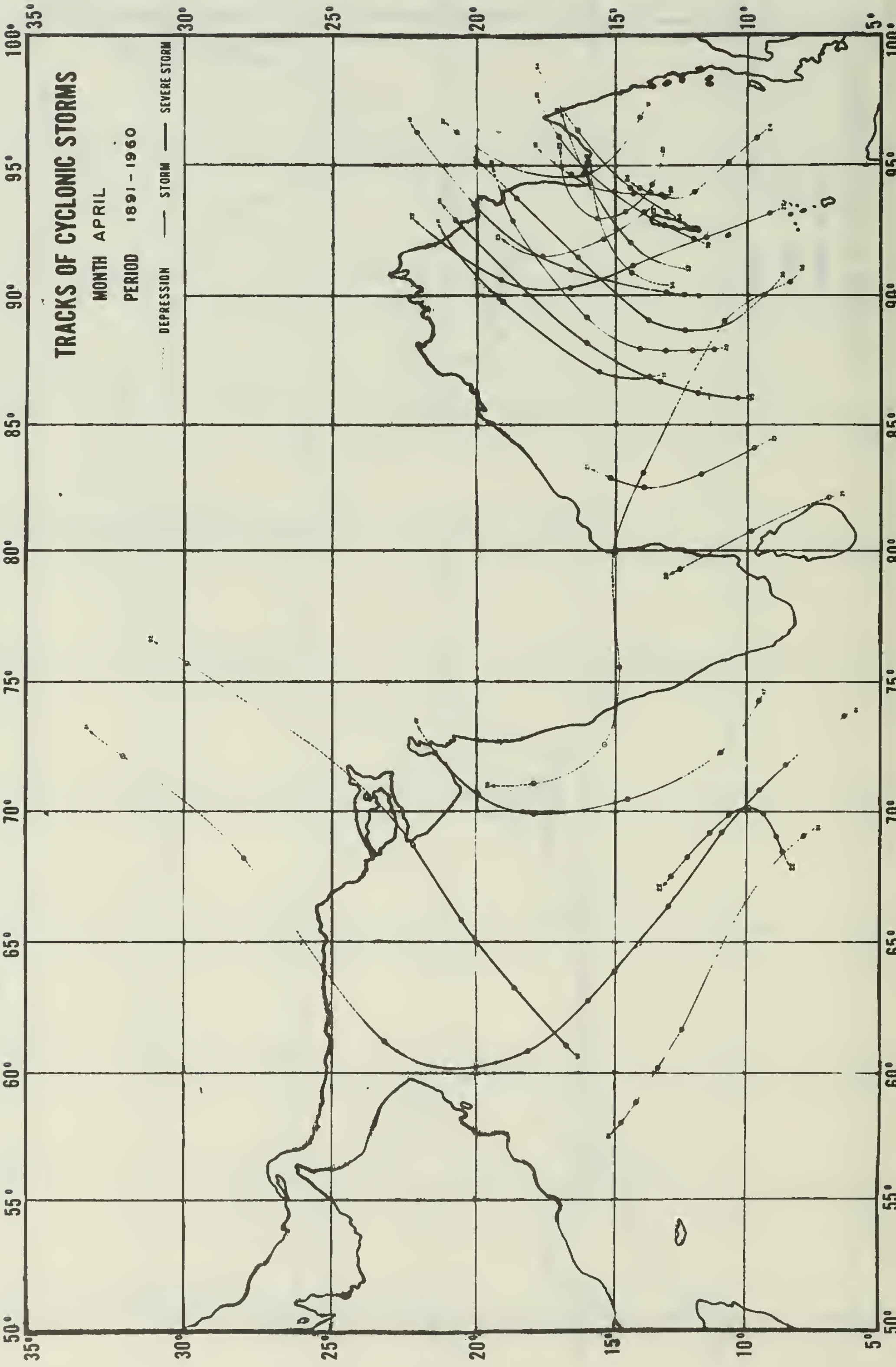
20°
15°
10°
5°

Figure A-3


TRACKS OF CYCLONIC STORMS
MONTH APRIL
PERIOD 1891-1960
DEPRESSION
STORM
SEVERE STORM
35°
30°
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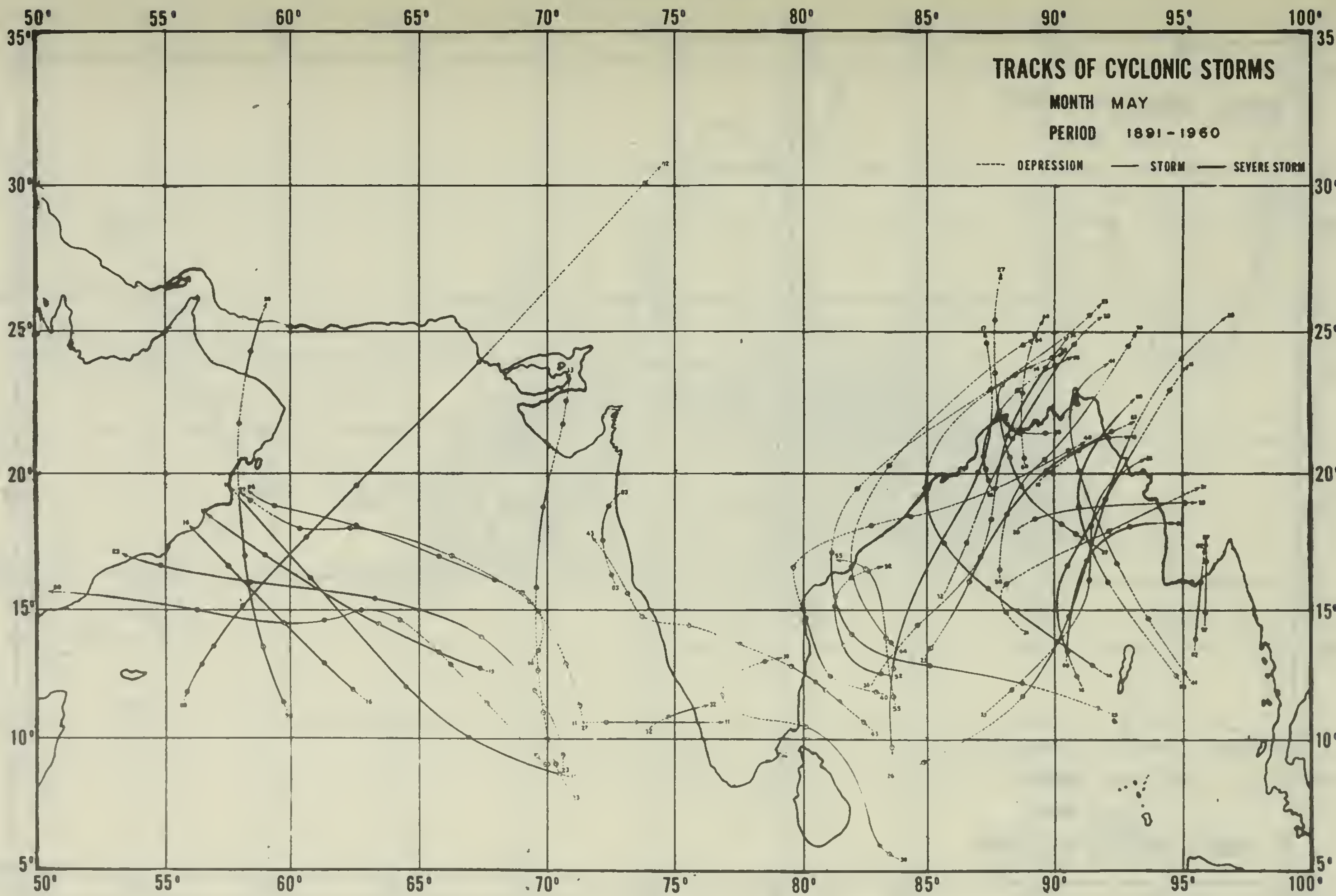
90°
95°
100°

Figure A-4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MONTH MAY
PERIOD 1891-1960
DEPRESSION
STORM
SEVERE STORM
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60°
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100°
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30°
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20°
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10°
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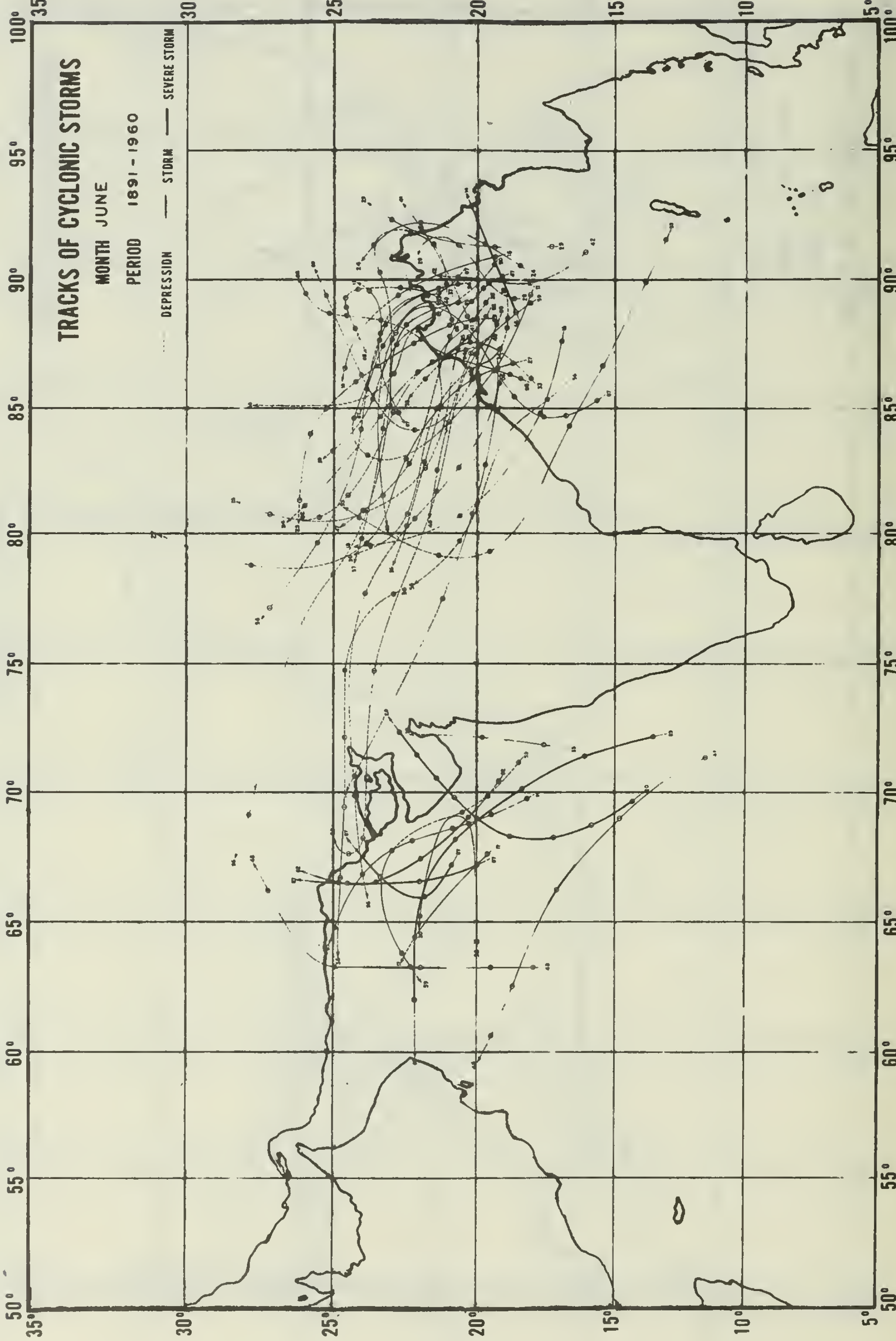
Figure A-5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MONTH JUNE
PERIOD 1891-1960
DEPRESSION
STORM
SEVERE STORM

Figure A-6

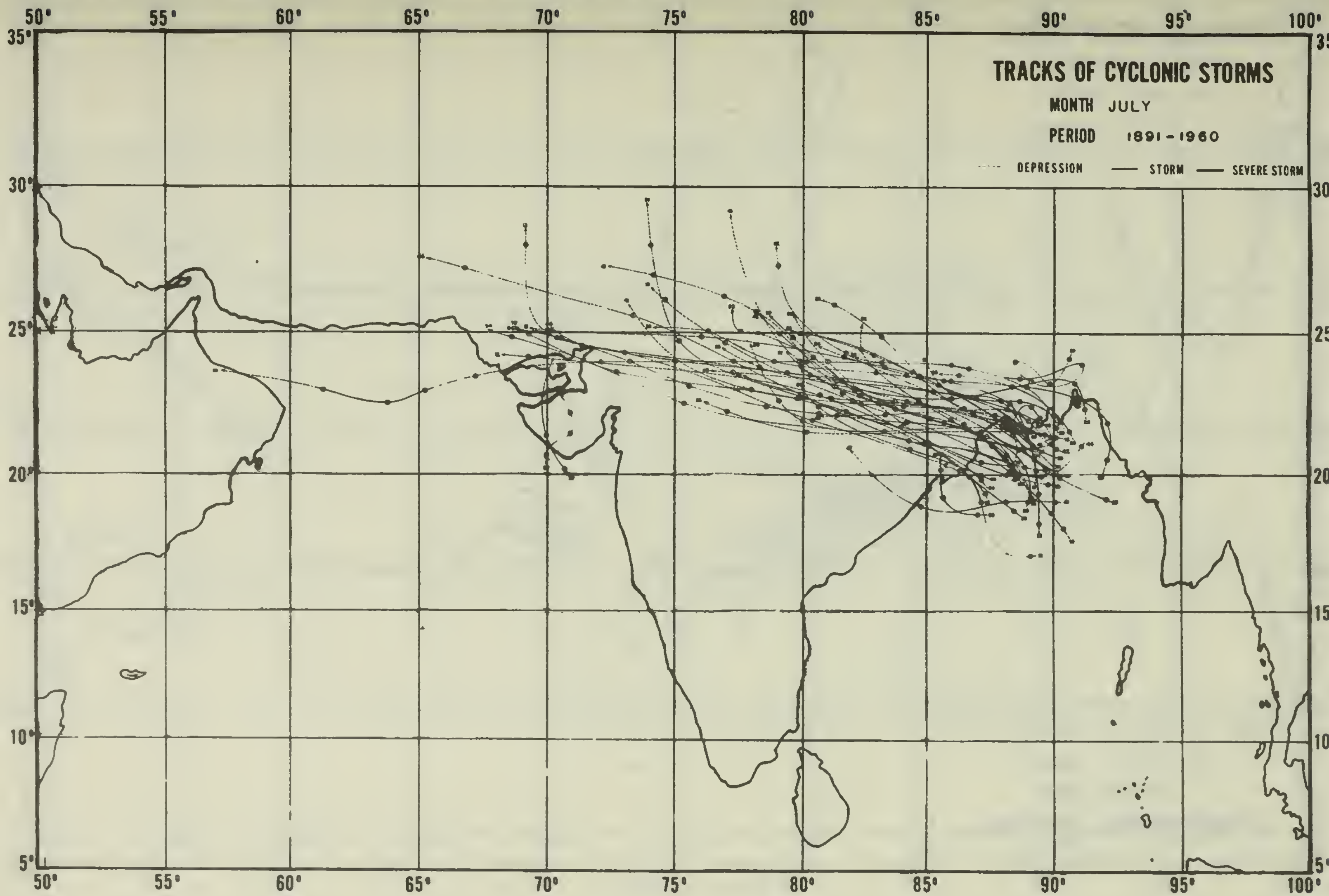
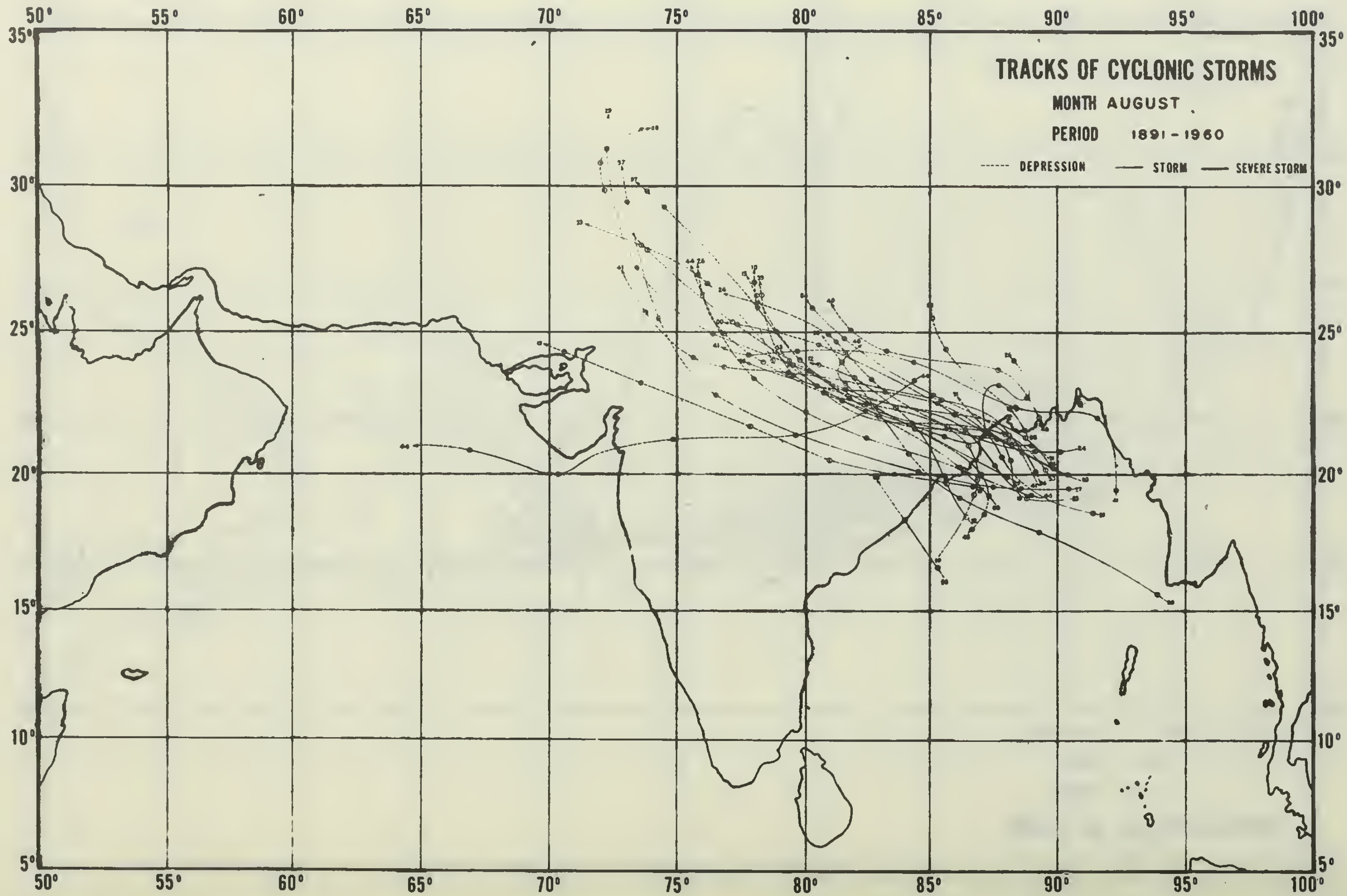

TRACKS OF CYCLONIC STORMS
MONTH JULY
PERIOD 1891-1960
DEPRESSION
STORM
SEVERE STORM
50° 55° 60° 65° 70° 75° 80° 85° 90° 95° 100°
35° 30° 25° 20° 15° 10° 5°

Figure A-7


TRACKS OF CYCLONIC STORMS
MONTH AUGUST
PERIOD 1891 - 1960
DEPRESSION
STORM
SEVERE STORM
50°
55°
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100°
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30°
25°
20°
15°
10°
5°

Figure A-8

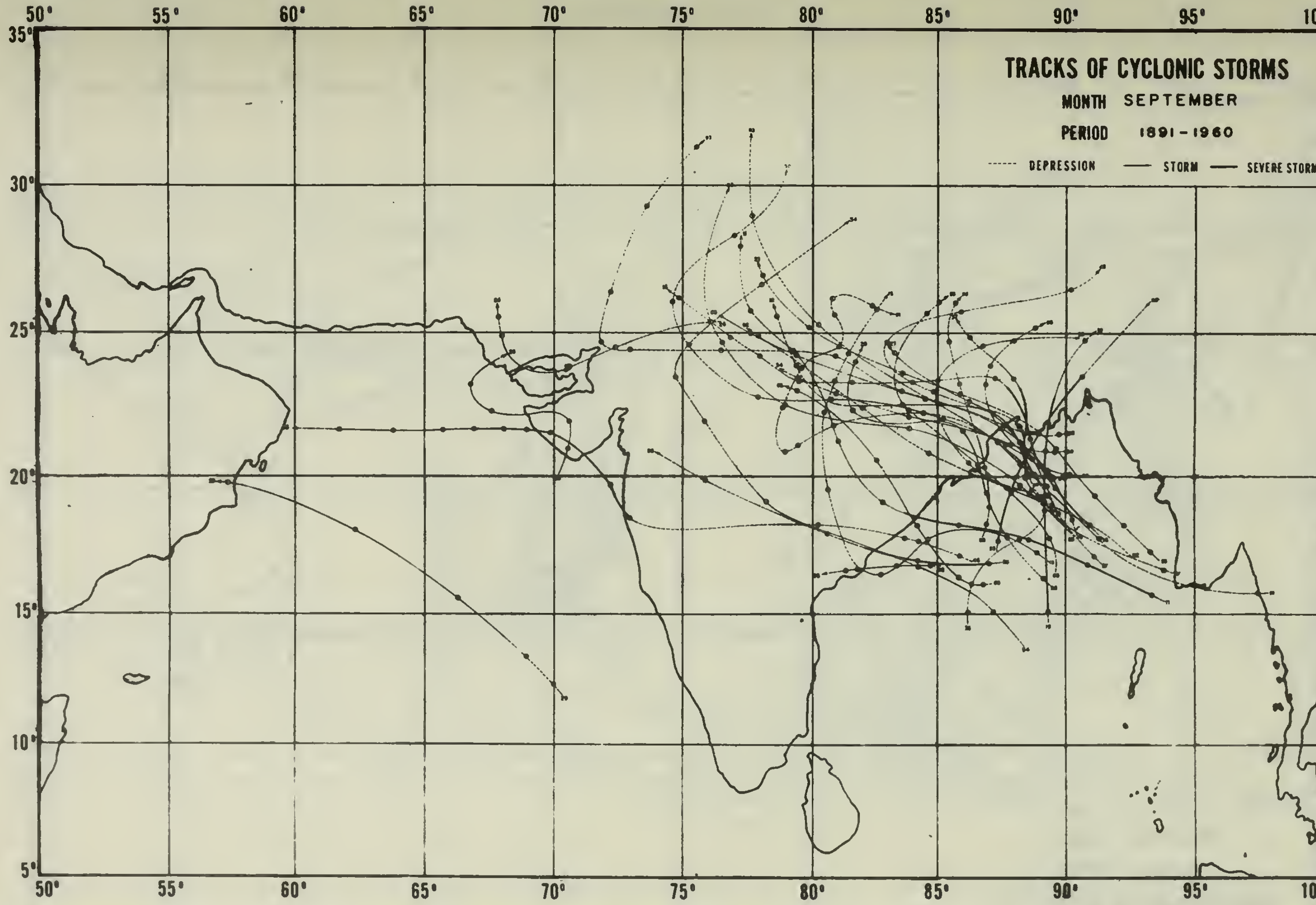
TRACKS OF CYCLONIC STORMS
MONTH SEPTEMBER
PERIOD 1891-1960
DEPRESSION
STORM
SEVERE STORM
50°
55°
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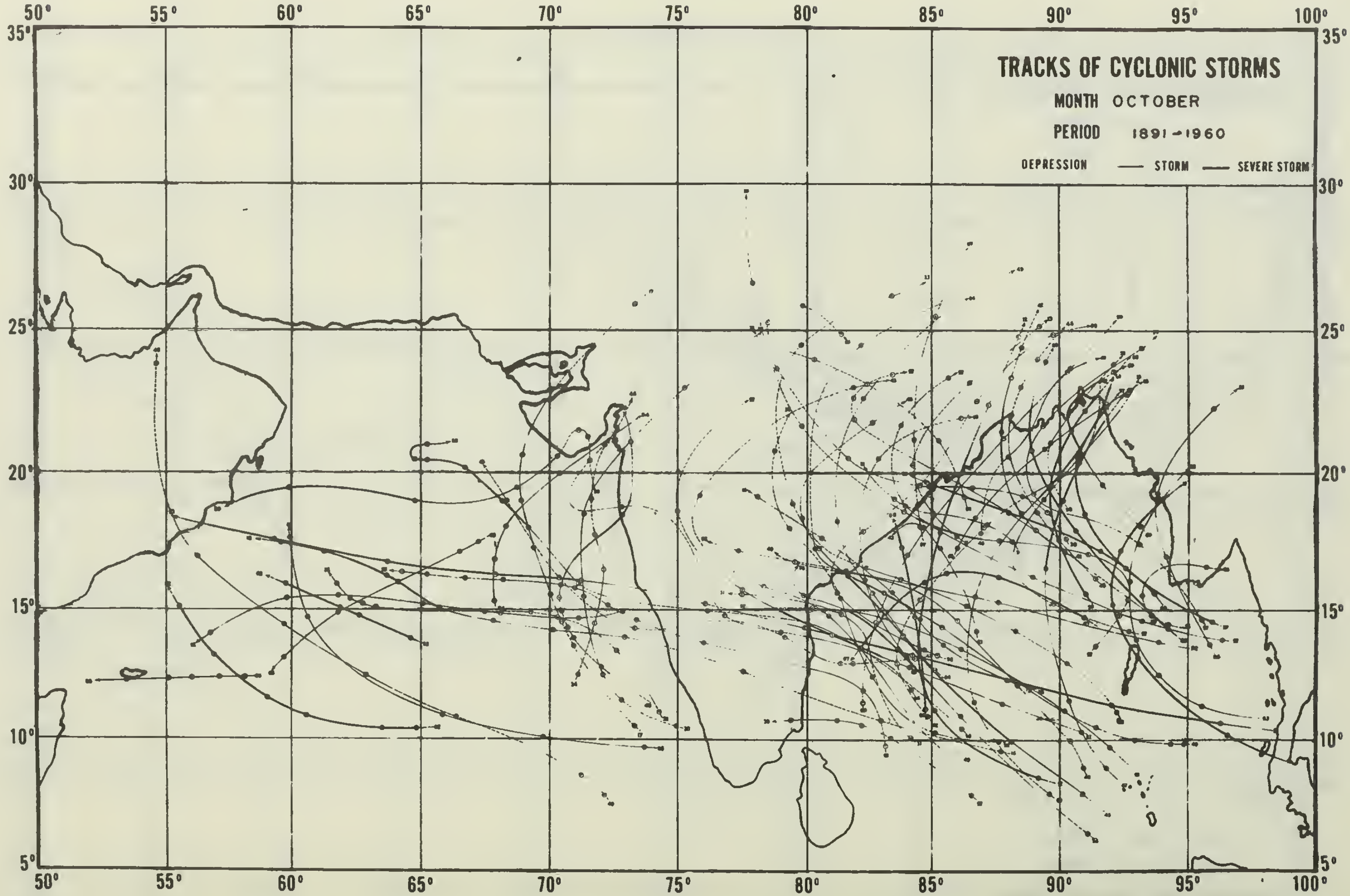
Figure A-9


TRACKS OF CYCLONIC STORMS
MONTH OCTOBER
PERIOD 1891-1960
DEPRESSION
STORM
SEVERE STORM
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10°
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Figure A-10

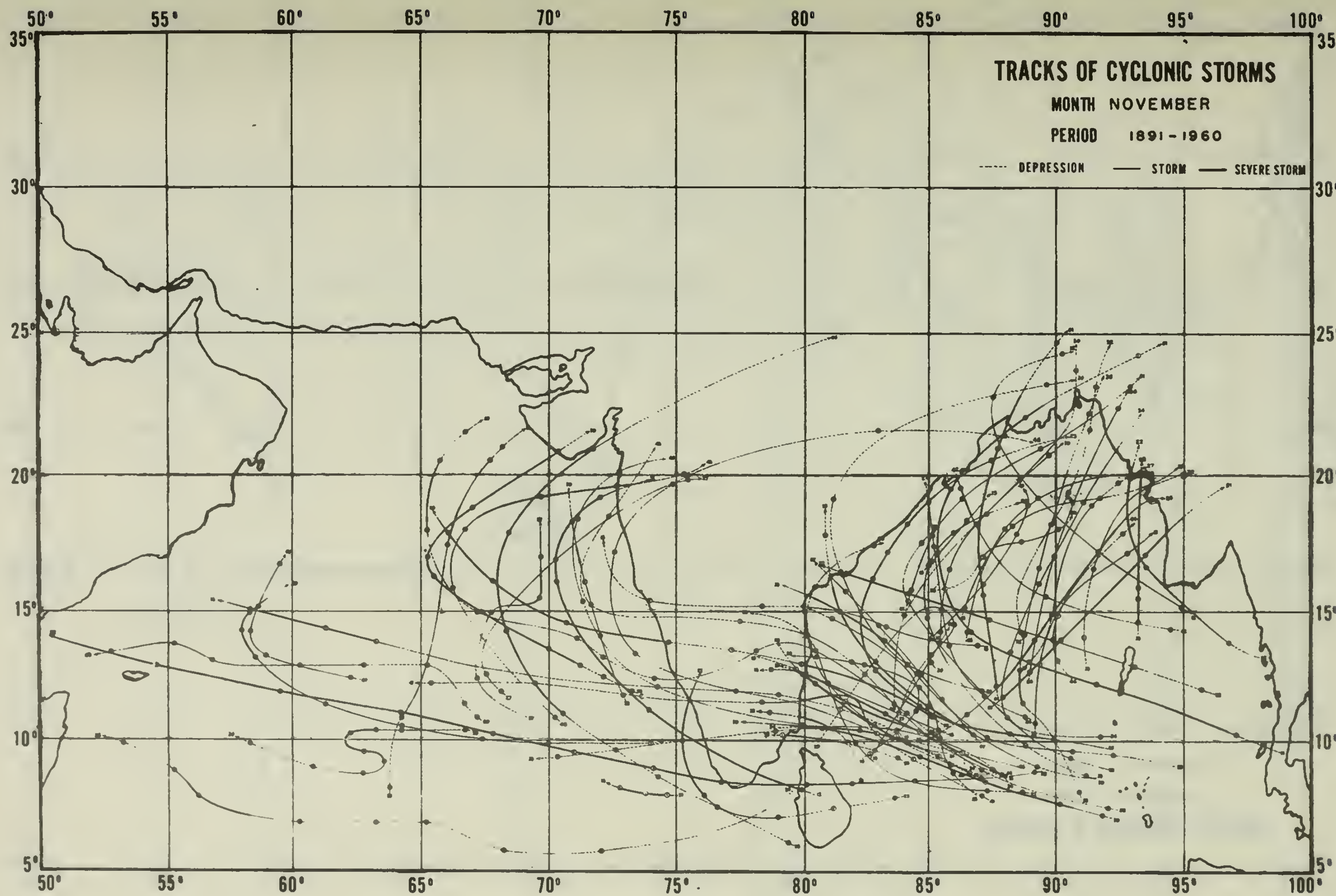

TRACKS OF CYCLONIC STORMS
MONTH NOVEMBER
PERIOD 1891 - 1960
DEPRESSION
STORM
SEVERE STORM
50° 55° 60° 65° 70° 75° 80° 85° 90° 95° 100°
35° 30° 25° 20° 15° 10° 5°

Figure A-11

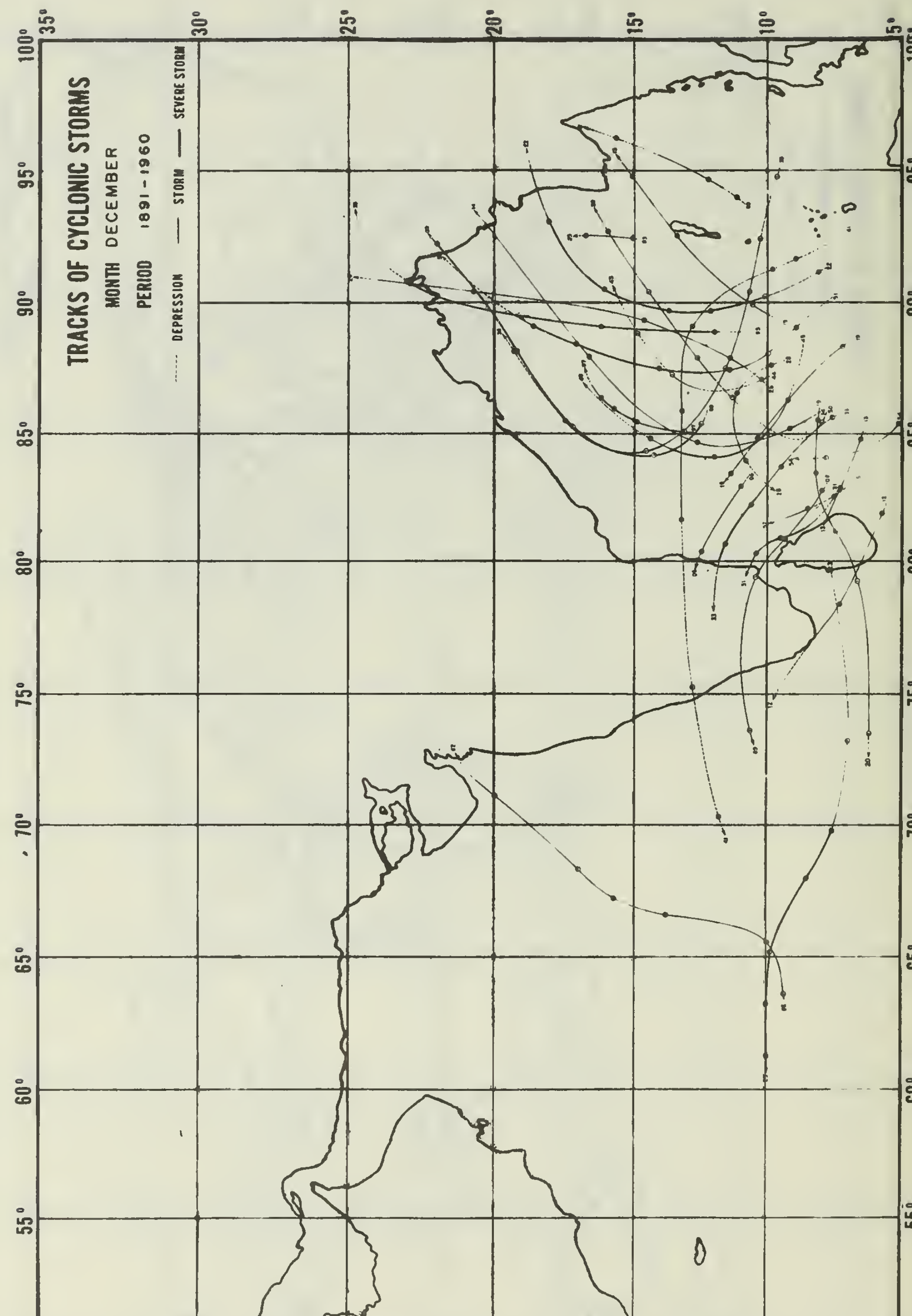

TRACKS OF CYCLONIC STORMS
MONTH DECEMBER
PERIOD 1891-1960
DEPRESSION
STORM
SEVERE STORM

Figure A-12

APPENDIX B

MONTHLY MEAN CHARTS FOR THE BAY OF BENGAL

CONTENTS

Figure B-6. Streamline charts for October (from Ramage and Raman, 1972)
(a) 850 mb
(b) 700 mb
(c) 500 mb
(d) 300 mb
(e) 200 mb
(f) 100 mb

Figure B-7. Mean cloud amount in Oktas
(a) January
(b) May
(c) July
(d) October

Figures B-8(a) through B-8(l). Percentage frequency of observations reporting precipitation, by month (from U.S. Navy Hydrographic Office, 1960 H. O. Pub. SP53).

Figures B-9(a) through B-9(l). Sea-surface temperatures, by month (unpublished data provided by Mrs. M. Robinson, Scripps Institution of Oceanography, La Jolla, Calif.).

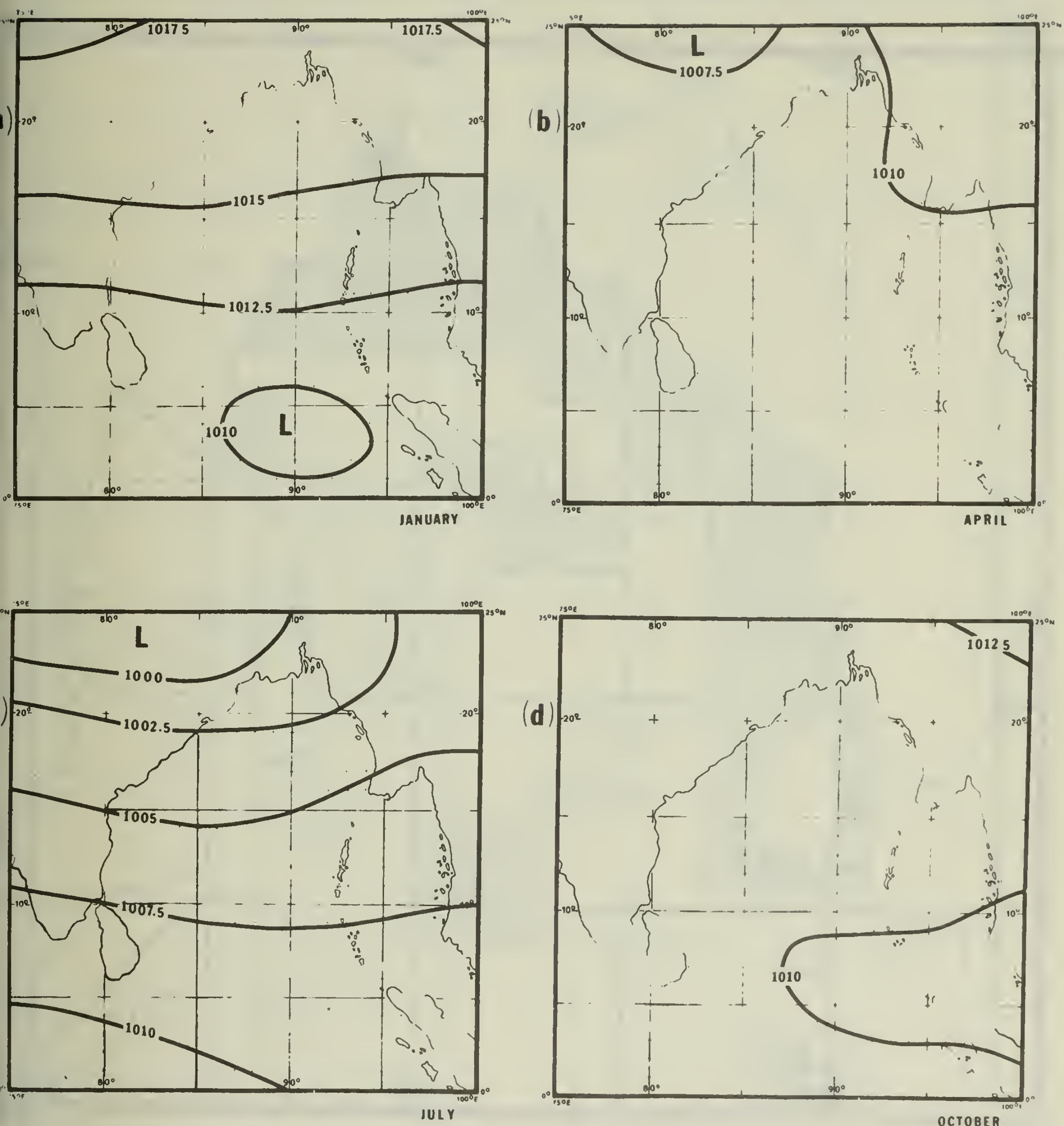


Figure B-1. Mean sea-level pressure

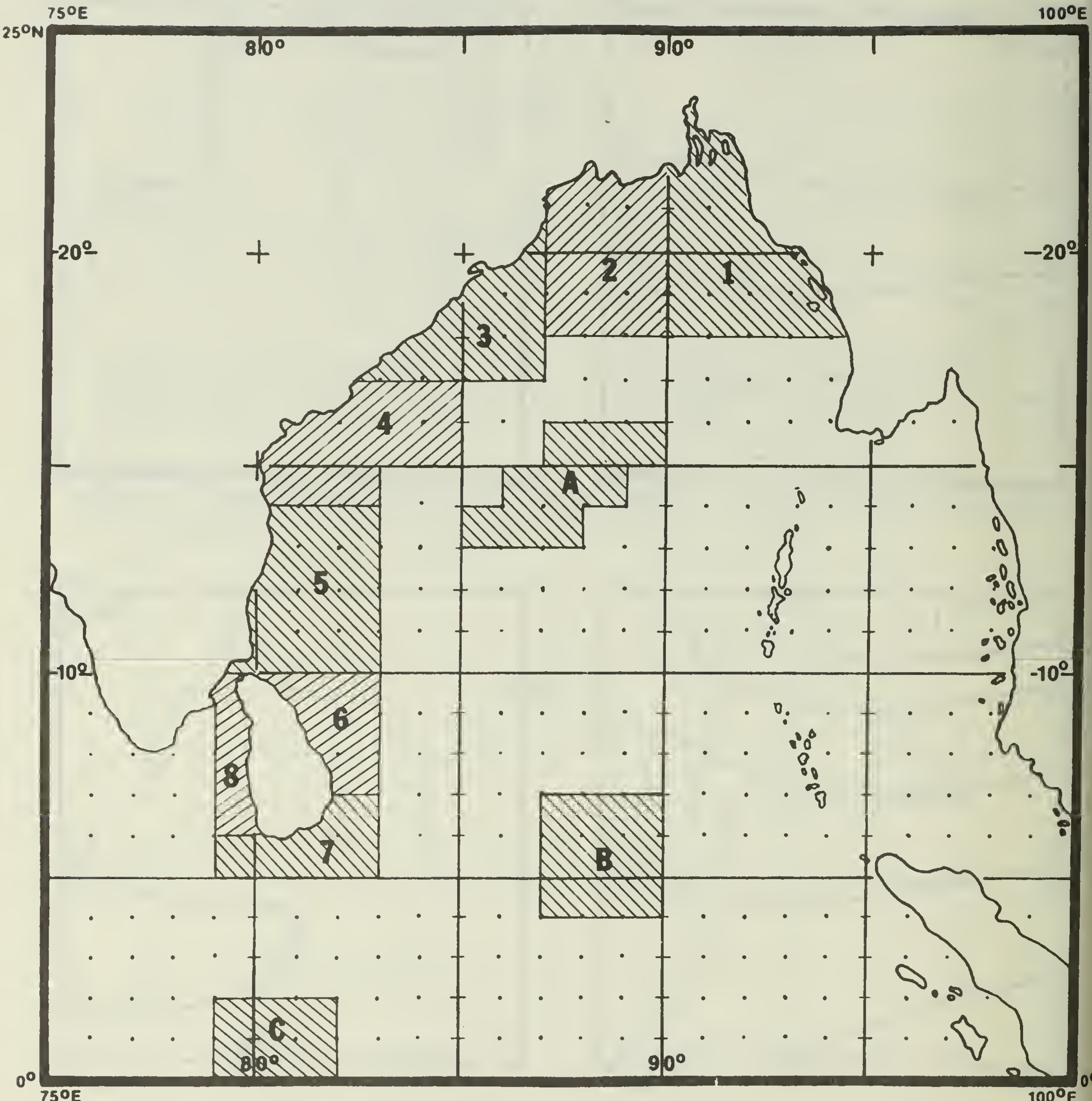


Figure B-2(a). Areas used for surface wind roses. Note: Data for areas A, B and C extracted from H. O. Pub. 64 (1966). Data for other areas extracted from SSMO (1971).

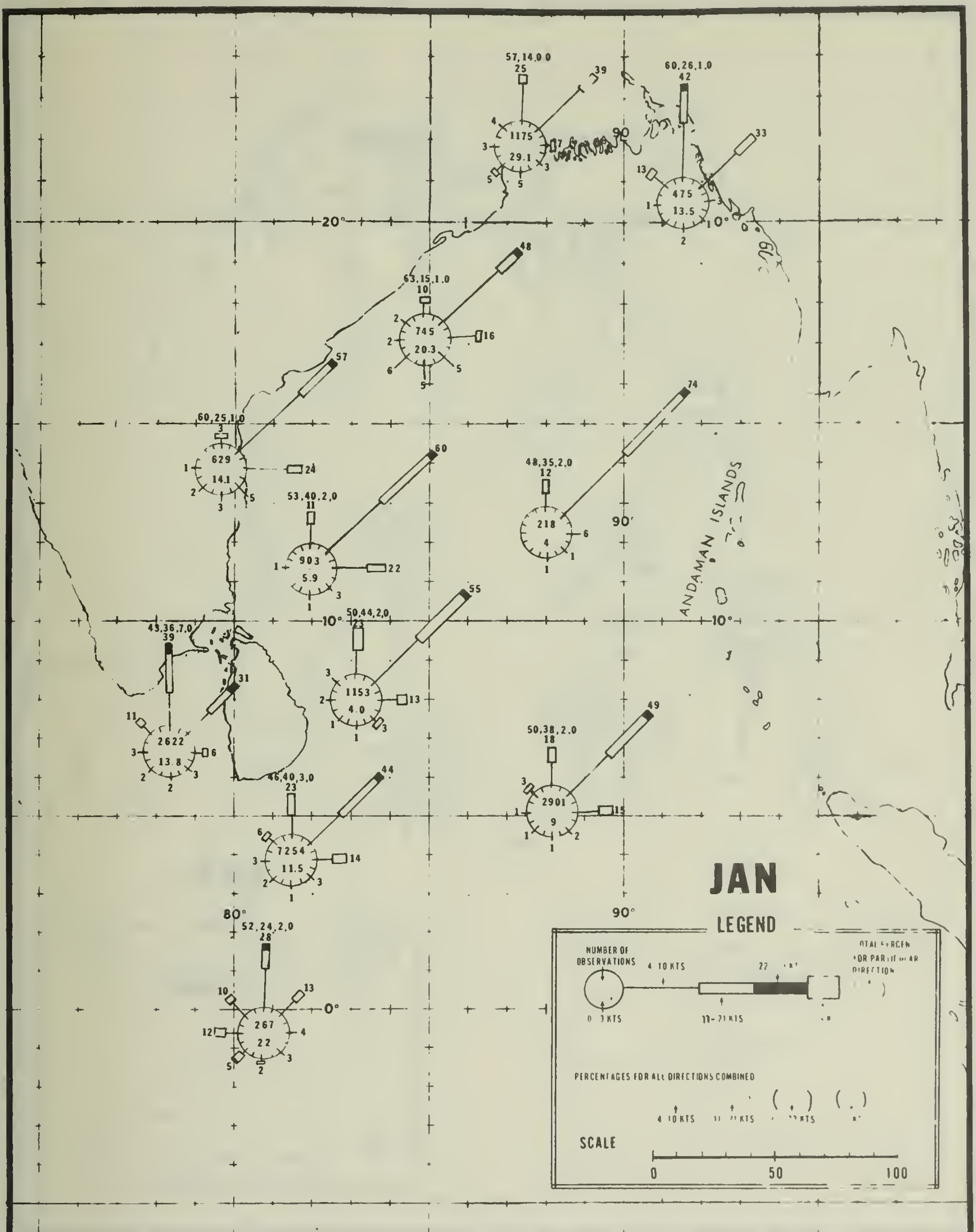
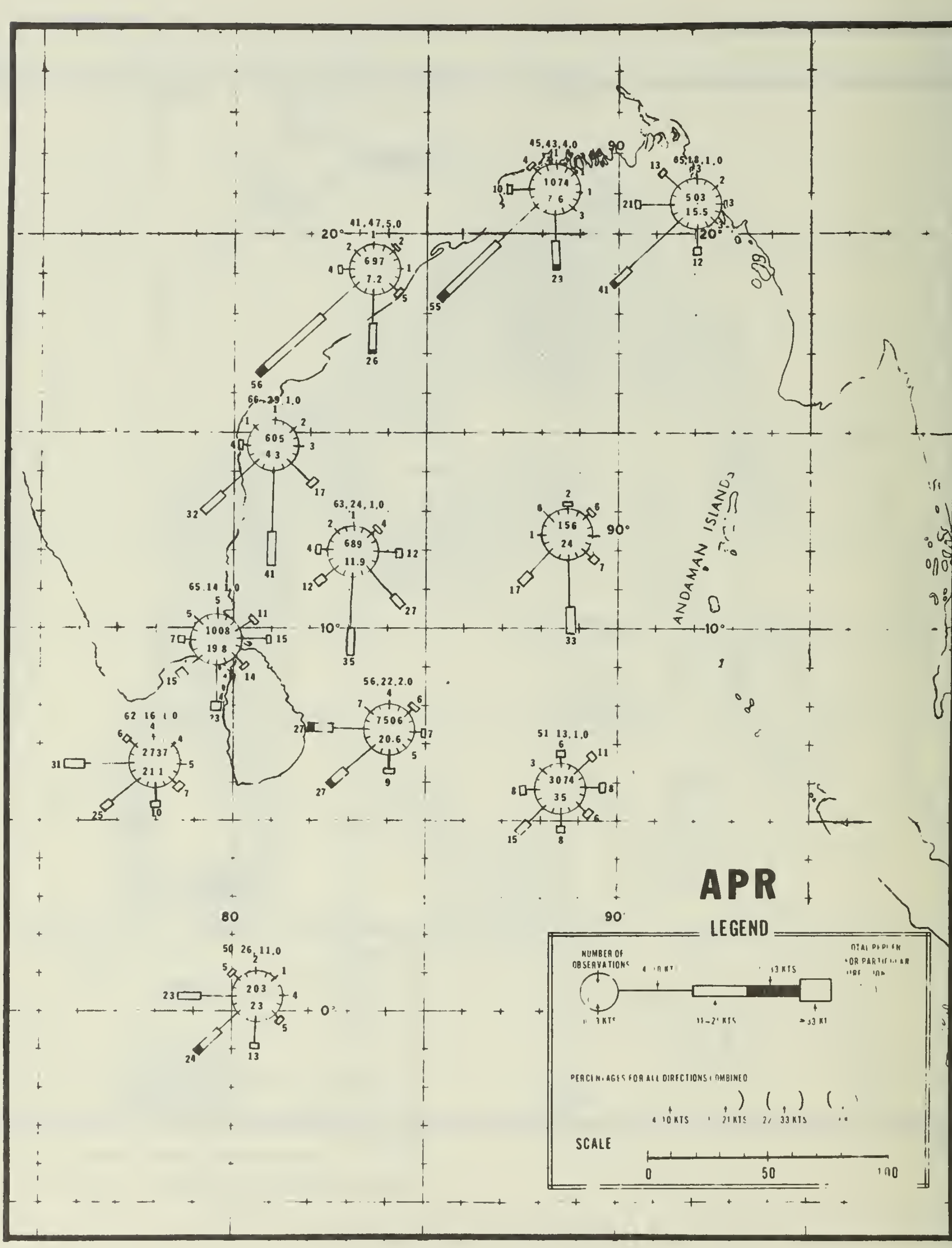
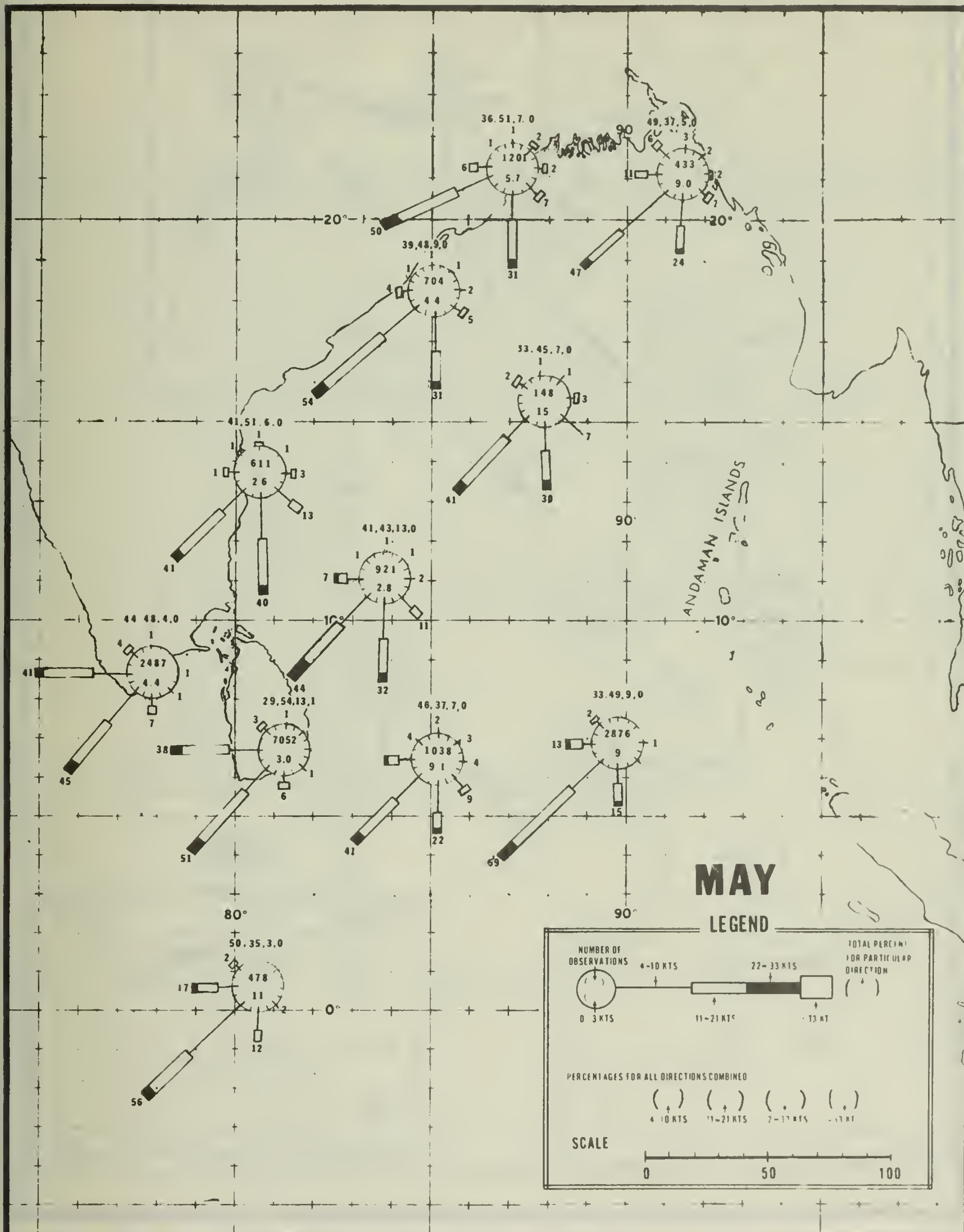

JAN
LEGEND
NUMBER OF OBSERVATIONS
4-10 KTS
11-21 KTS
0-3 KTS
PERCENTAGES FOR ALL DIRECTIONS COMBINED
SCALE
0
50
100
ANDAMAN ISLANDS
20°
10°
0°
80°
90°

Figure B-2(b)



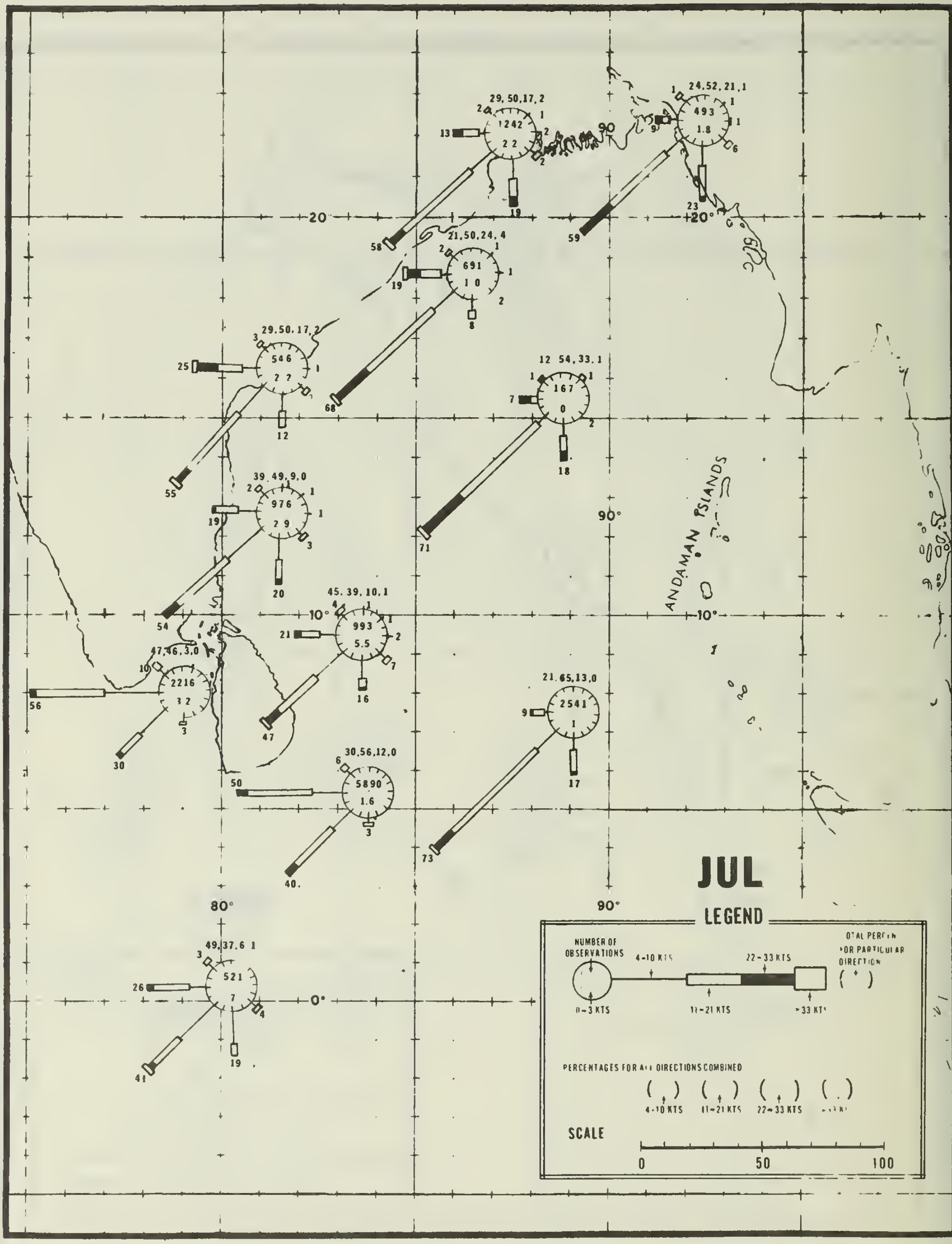
APR
LEGEND
NUMBER OF OBSERVATIONS
PERCENTAGES FOR ALL DIRECTIONS COMBINED
SCALE
0
50
100
ANDAMAN ISLANDS
20°
10°
0°
80
90°

Figure B-2(c)



MAY
LEGEND
NUMBER OF OBSERVATIONS
4-10 KTS
22-33 KTS
0-3 KTS
11-21 KTS
PERCENTAGES FOR ALL DIRECTIONS COMBINED
SCALE
0
50
100
ANDAMAN ISLANDS
20°
10°
0°
80°
90°

Figure B-2(d)



JUL
LEGEND
NUMBER OF OBSERVATIONS
4-10 KTS
22-33 KTS
0-3 KTS
11-21 KTS
PERCENTAGES FOR ALL DIRECTIONS COMBINED
4-10 KTS
11-21 KTS
22-33 KTS
SCALE
0
50
100
ANDAMAN ISLANDS
20°
10°
0°
80°
90°

Figure B-2(e)

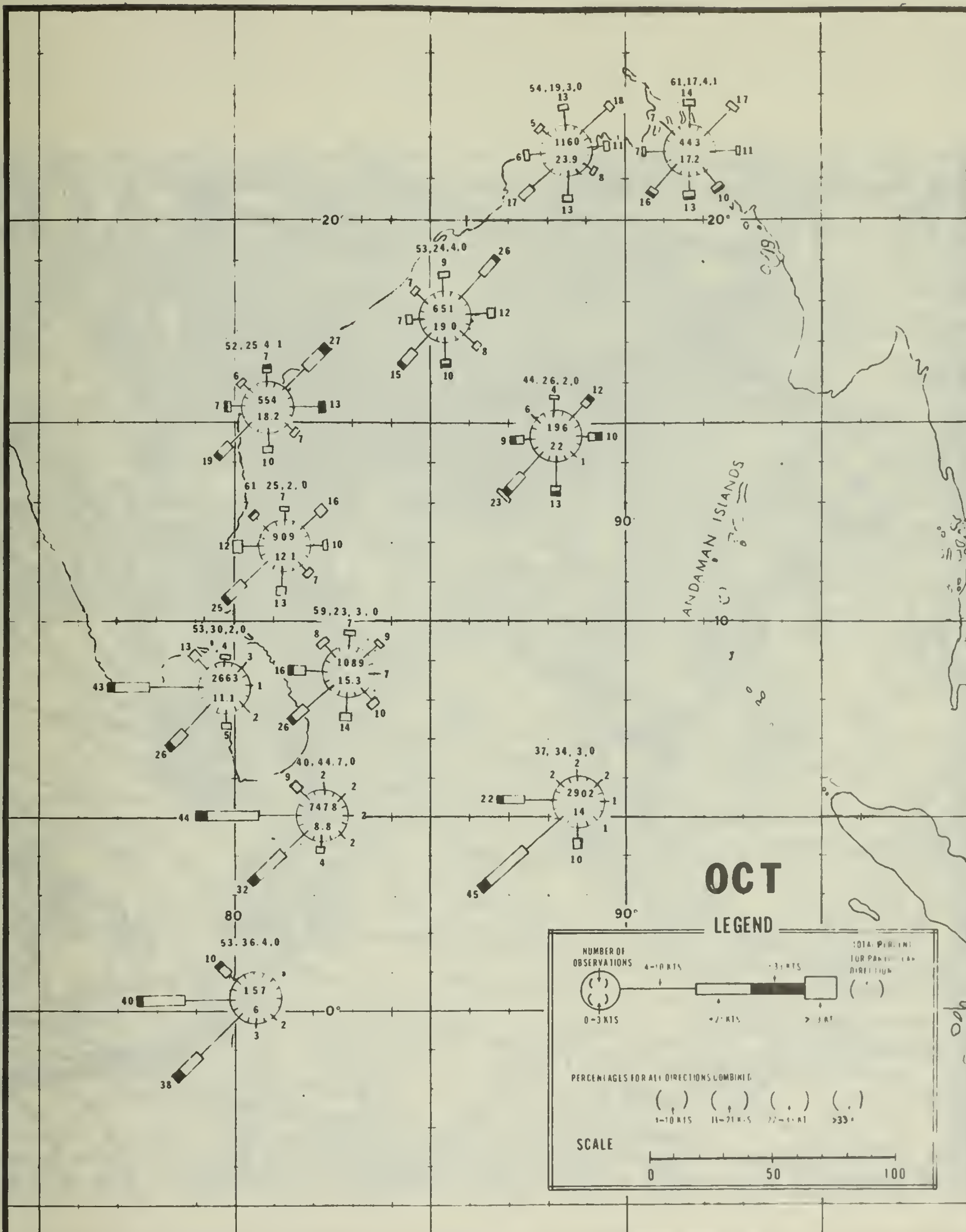

OCT
LEGEND
NUMBER OF OBSERVATIONS
0-3 KTS
PERCENTAGES FOR ALL DIRECTIONS COMBINED
SCALE
0
50
100
ANDAMAN ISLANDS
20°
90°
80
0°

Figure B-2(f)

Figure B-3(a). 850 mb streamline chart (JAN).

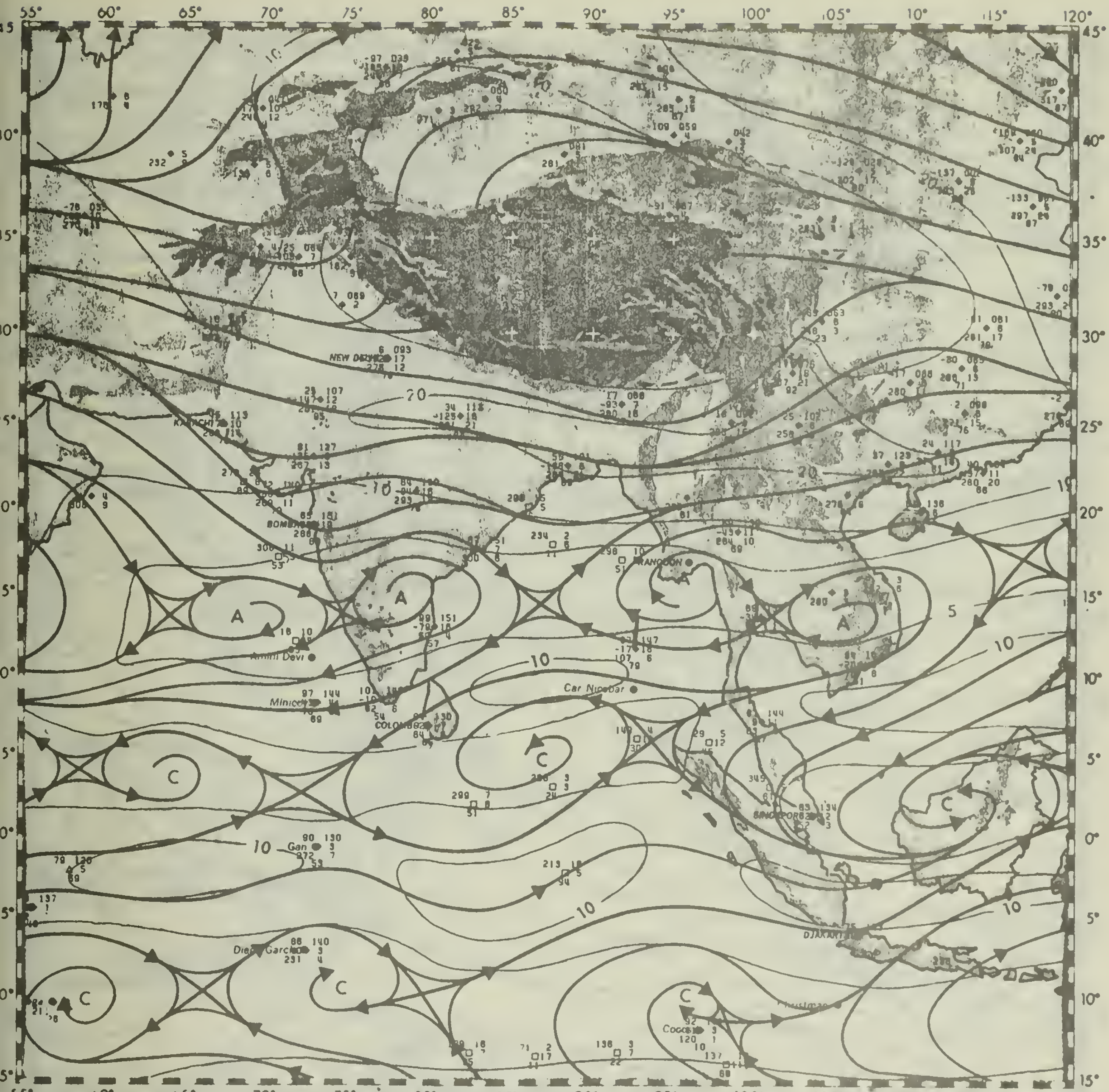


Figure B-3(b). 700 mb streamline chart (JAN).

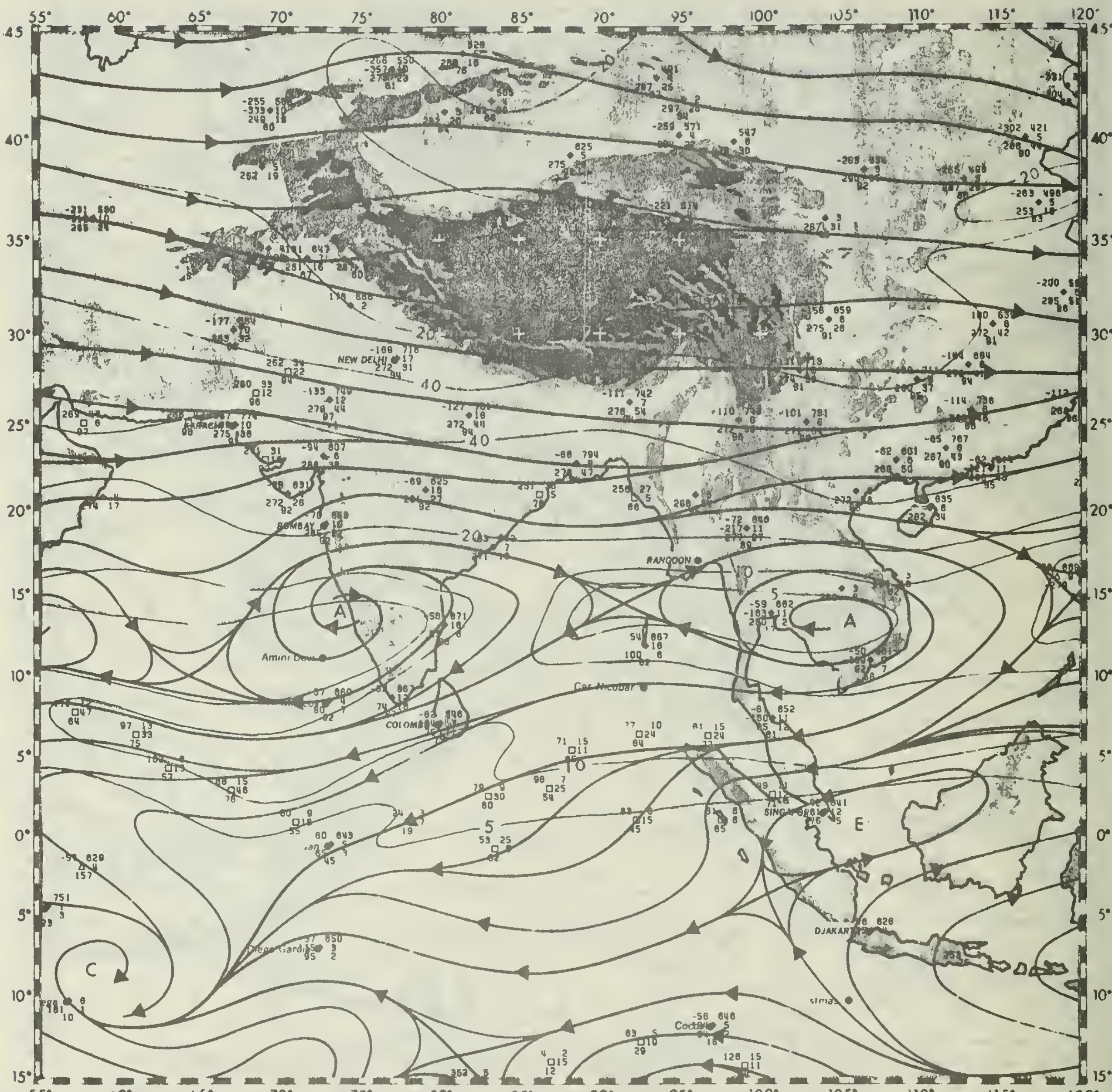


Figure B-3(c). 500 mb streamline chart (JAN).

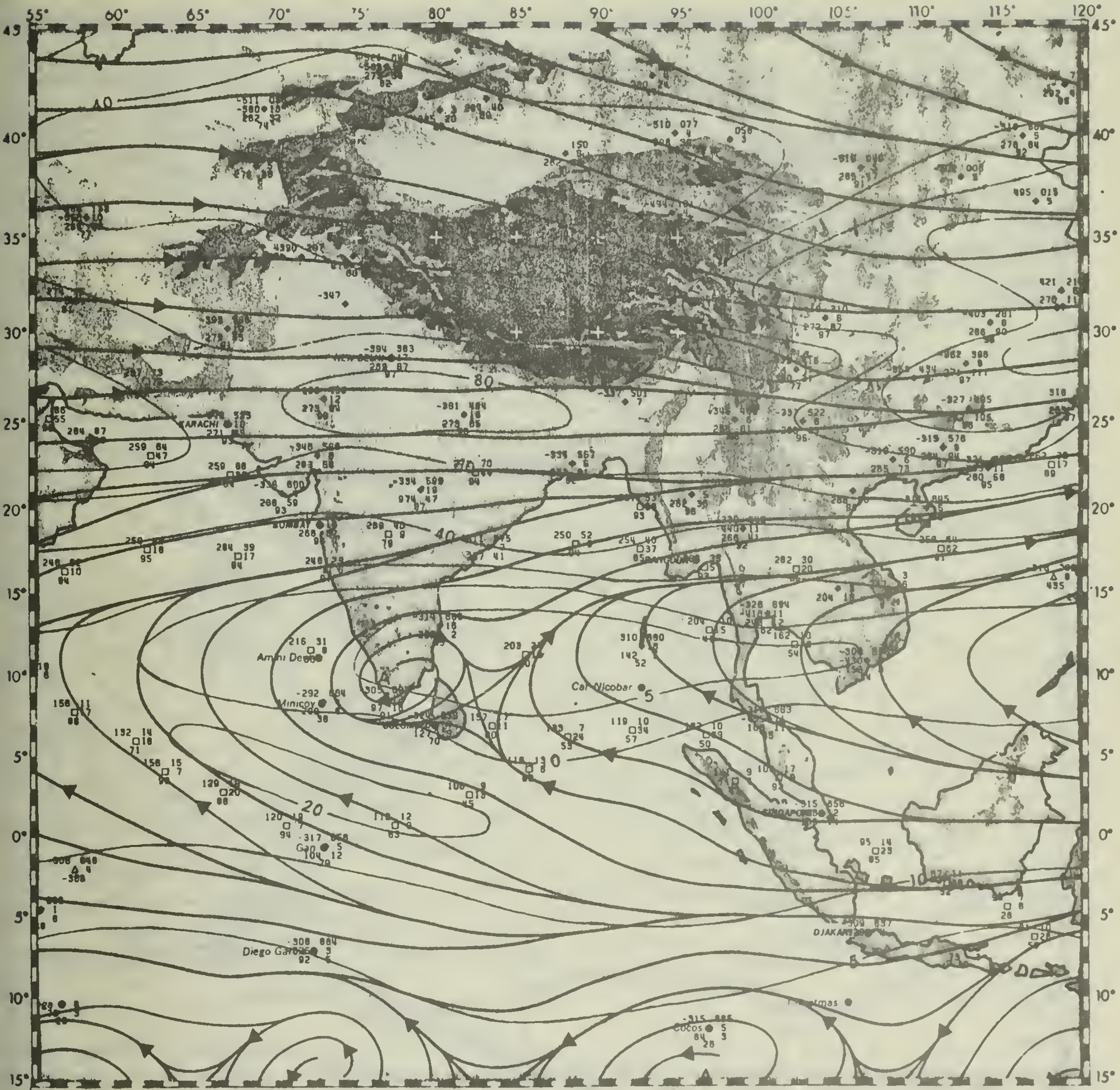


Figure B-3(d). 300 mb streamline chart (JAN).

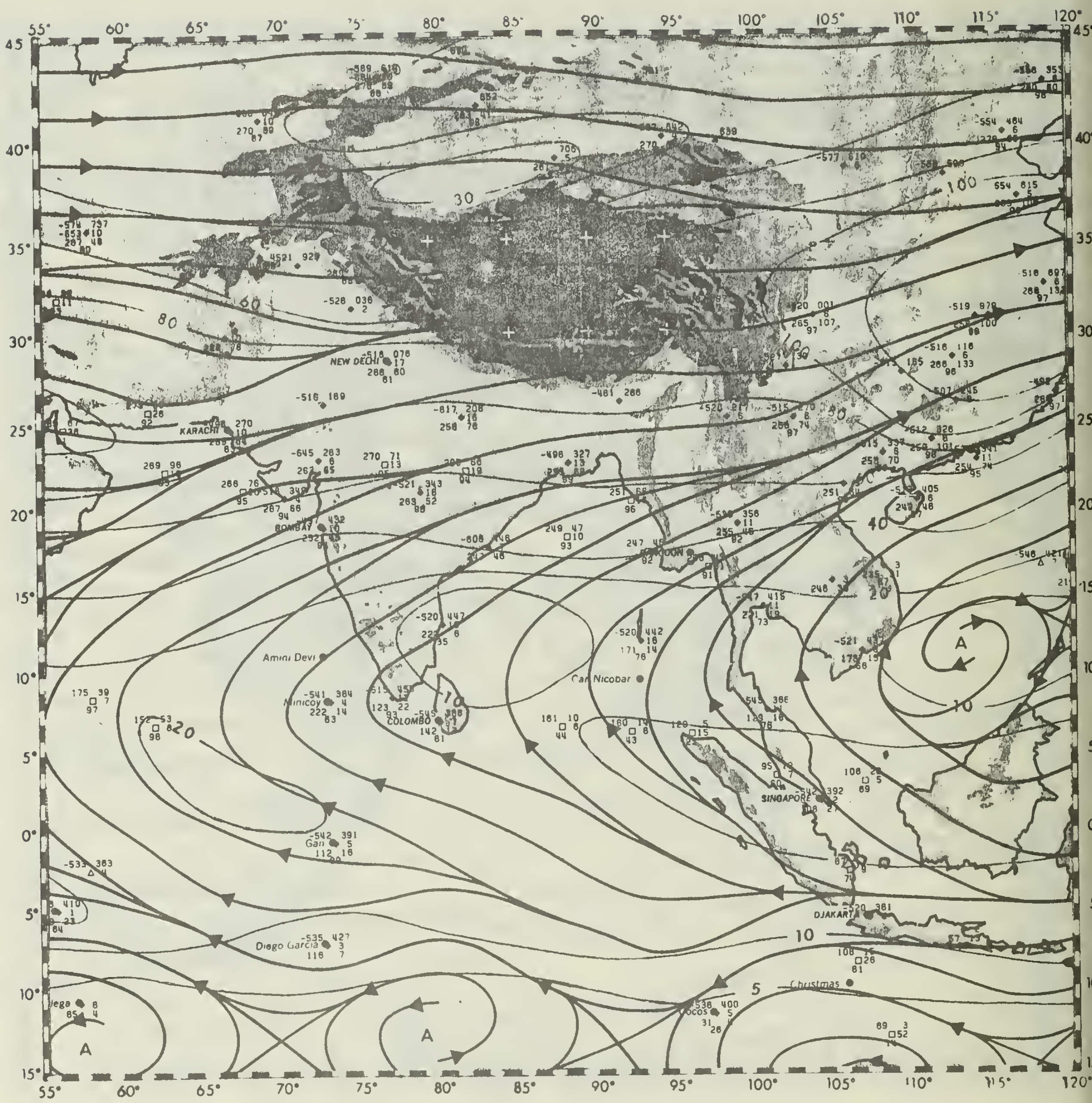


Figure B-3(e). 200 mb streamline chart (JAN).

Figure B-3(f). 100 mb streamline chart (JAN).

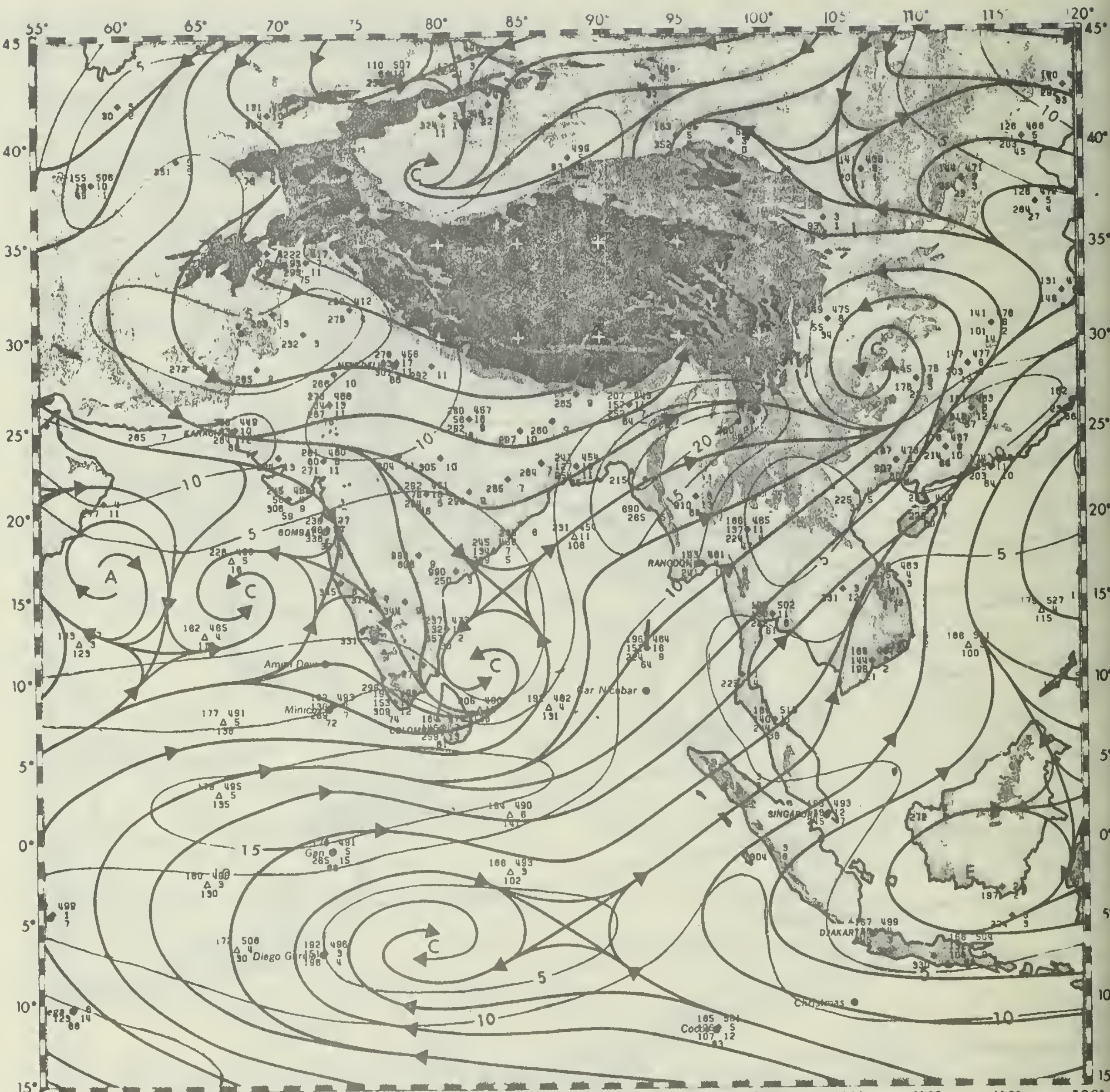


Figure B-4(a). 850 mb streamline chart (MAY).

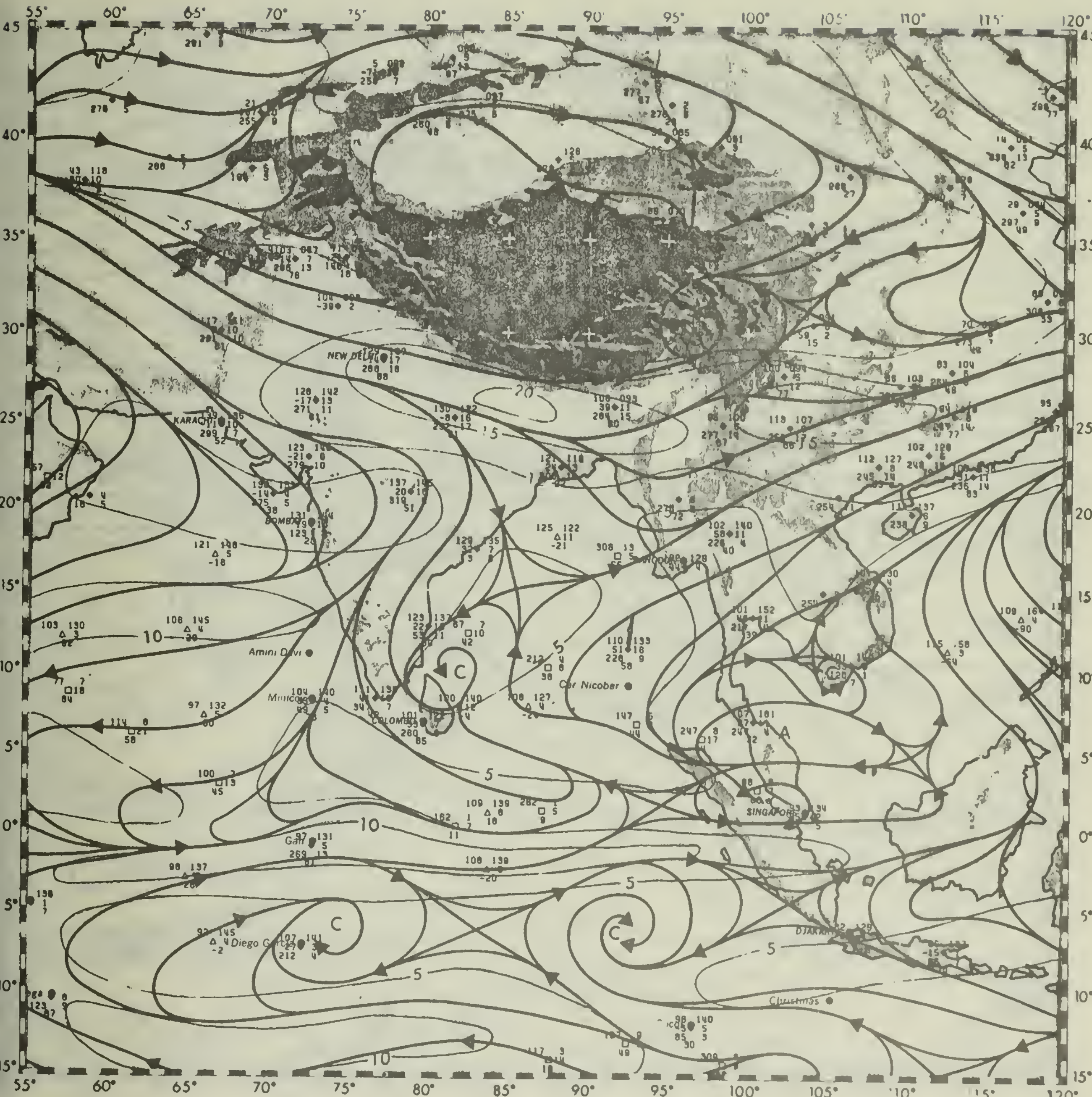


Figure B-4(b). 700 mb streamline chart (MAY).

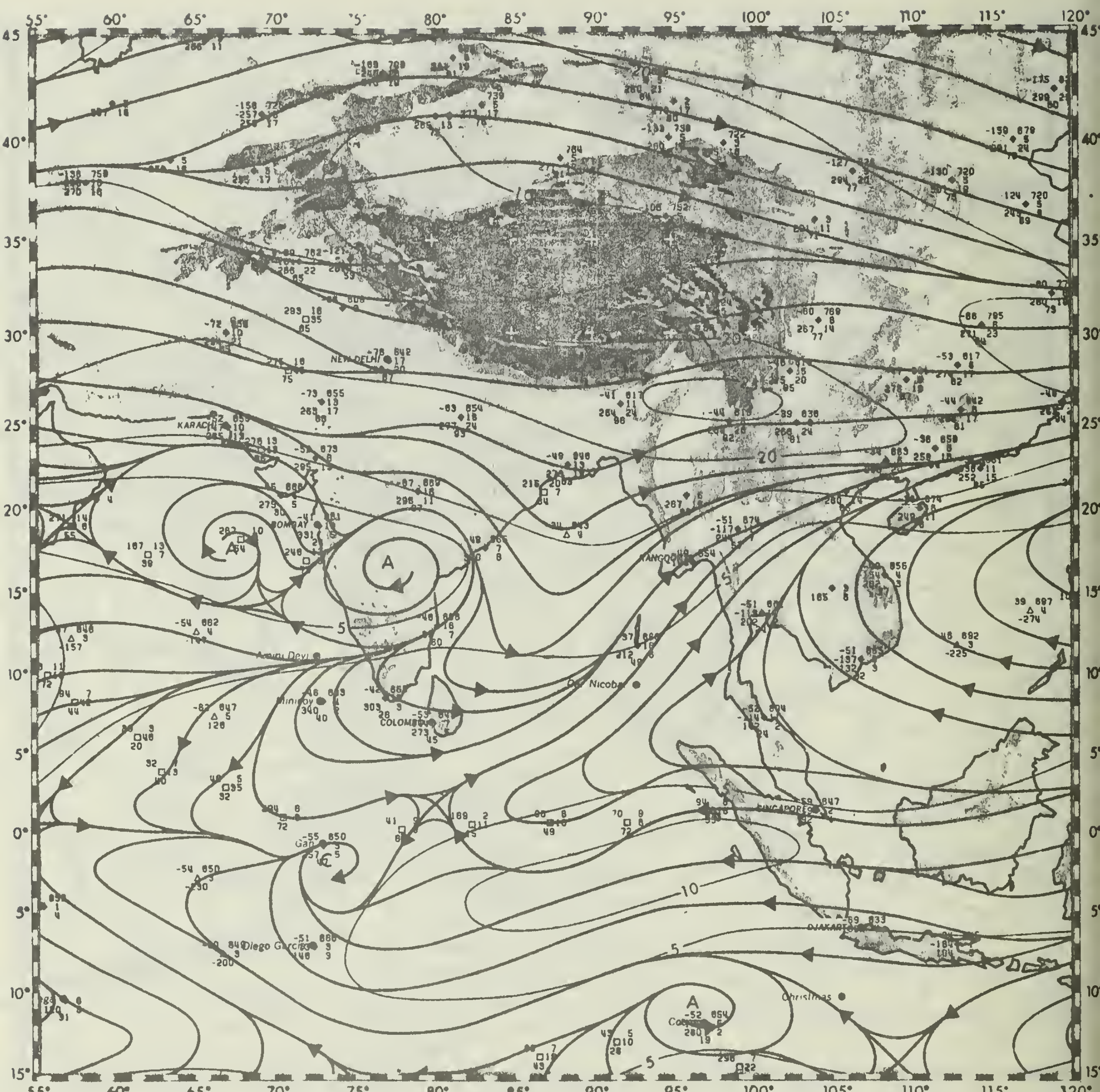


Figure B-4(c). 500 mb streamline chart (MAY).

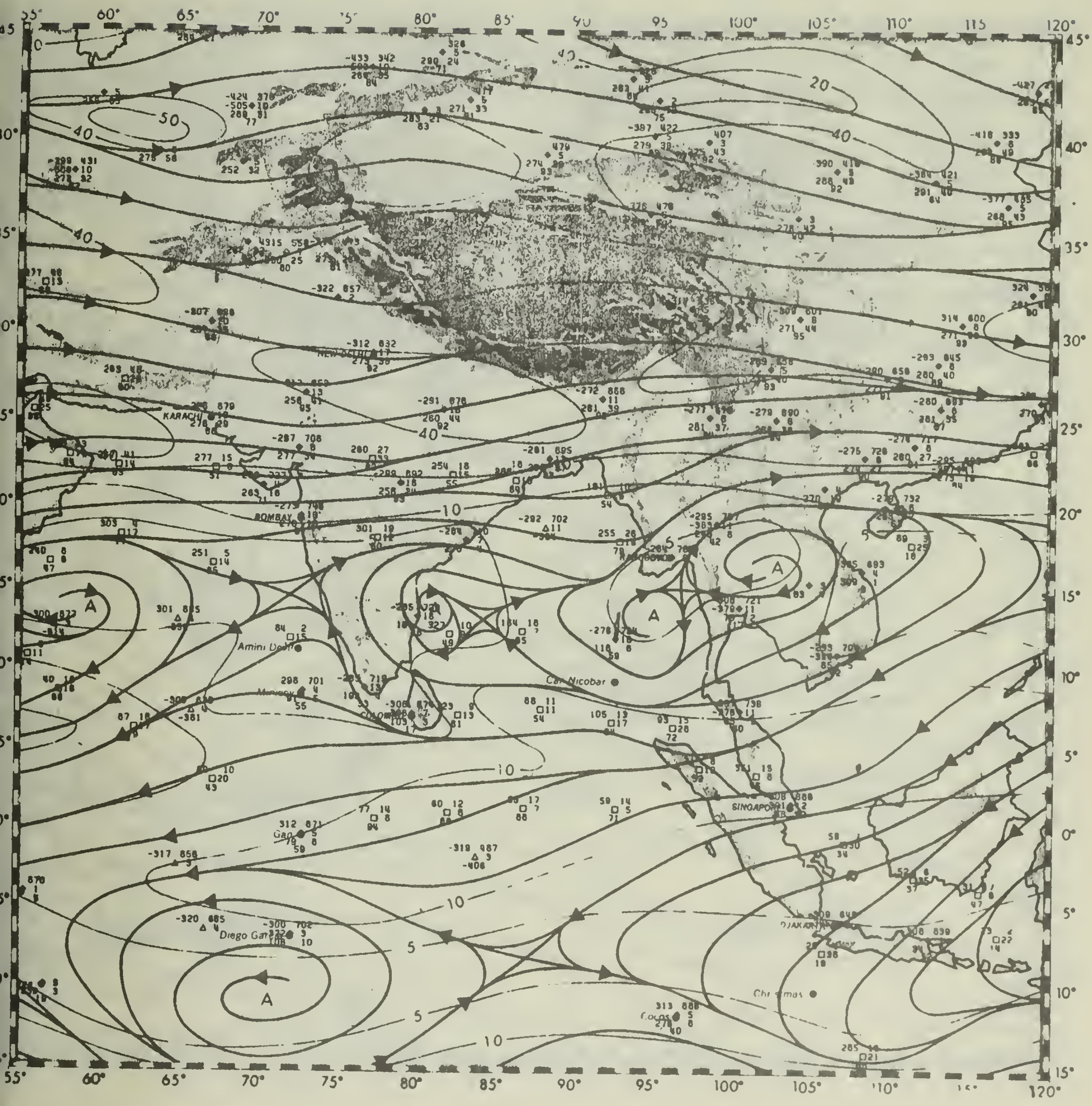


Figure B-4(d). 300 mb streamline chart (MAY).

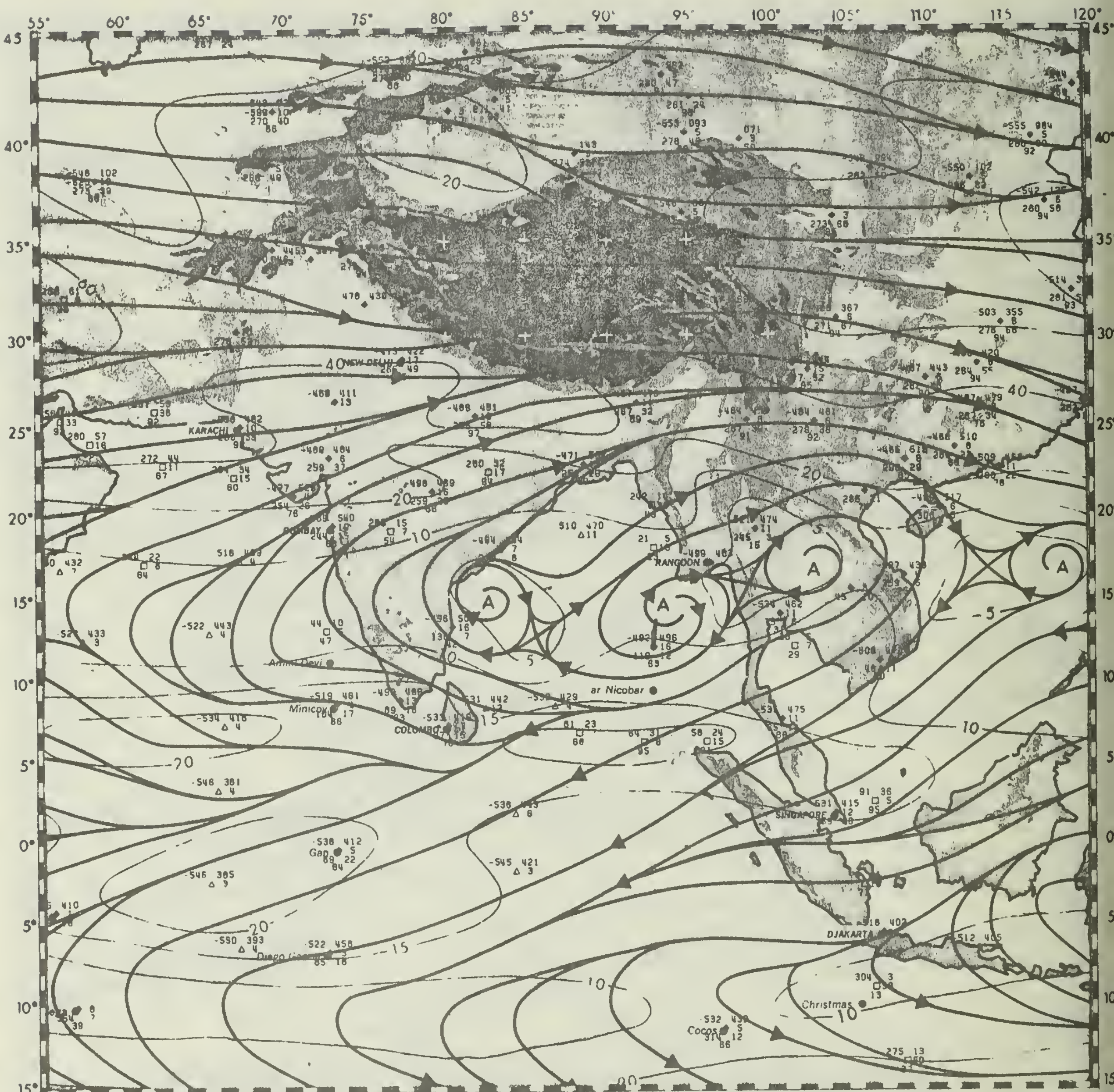


Figure B-4(e). 200 mb streamline chart (MAY).

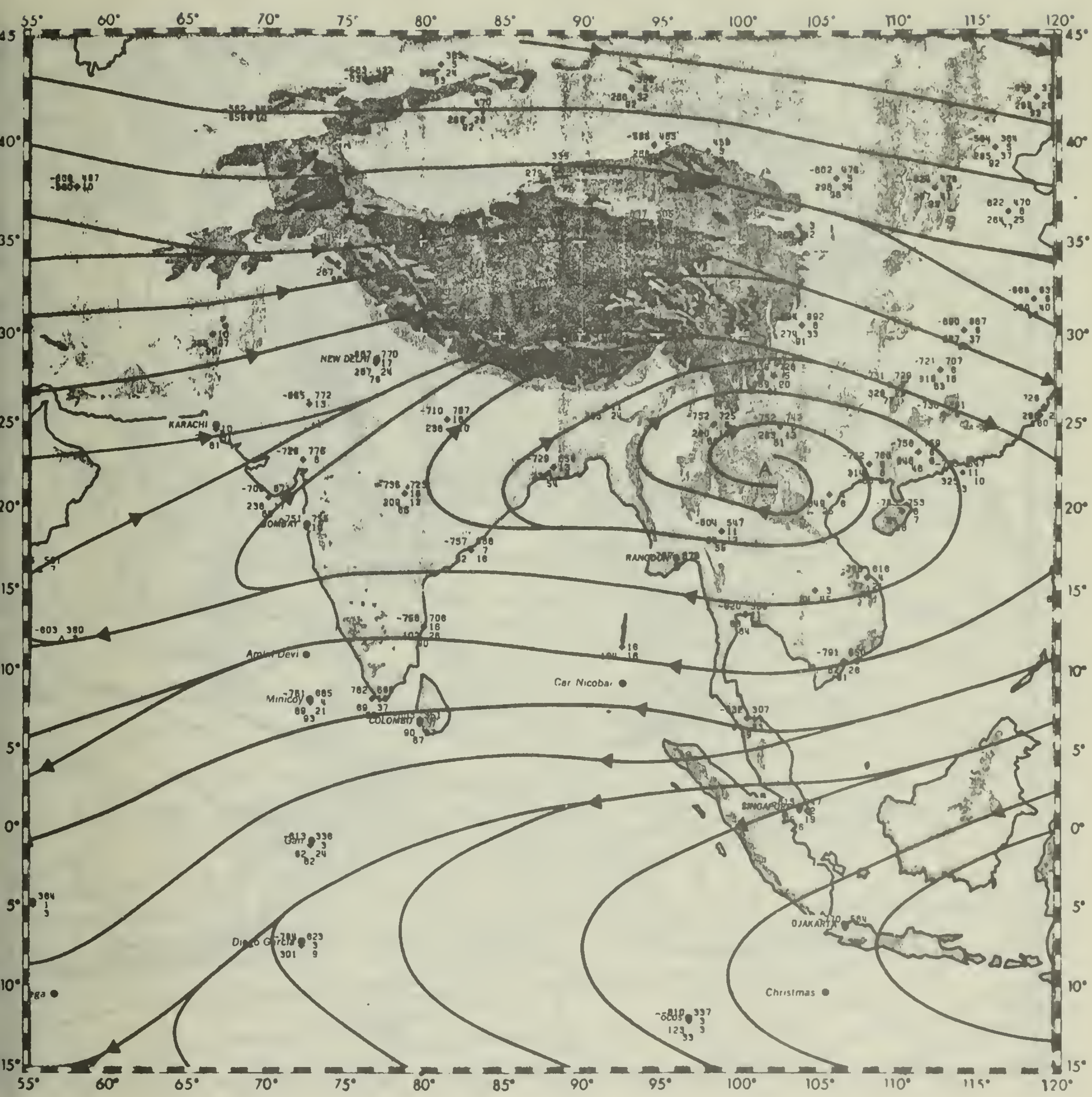


Figure B-4(f). 100 mb streamline chart (MAY).

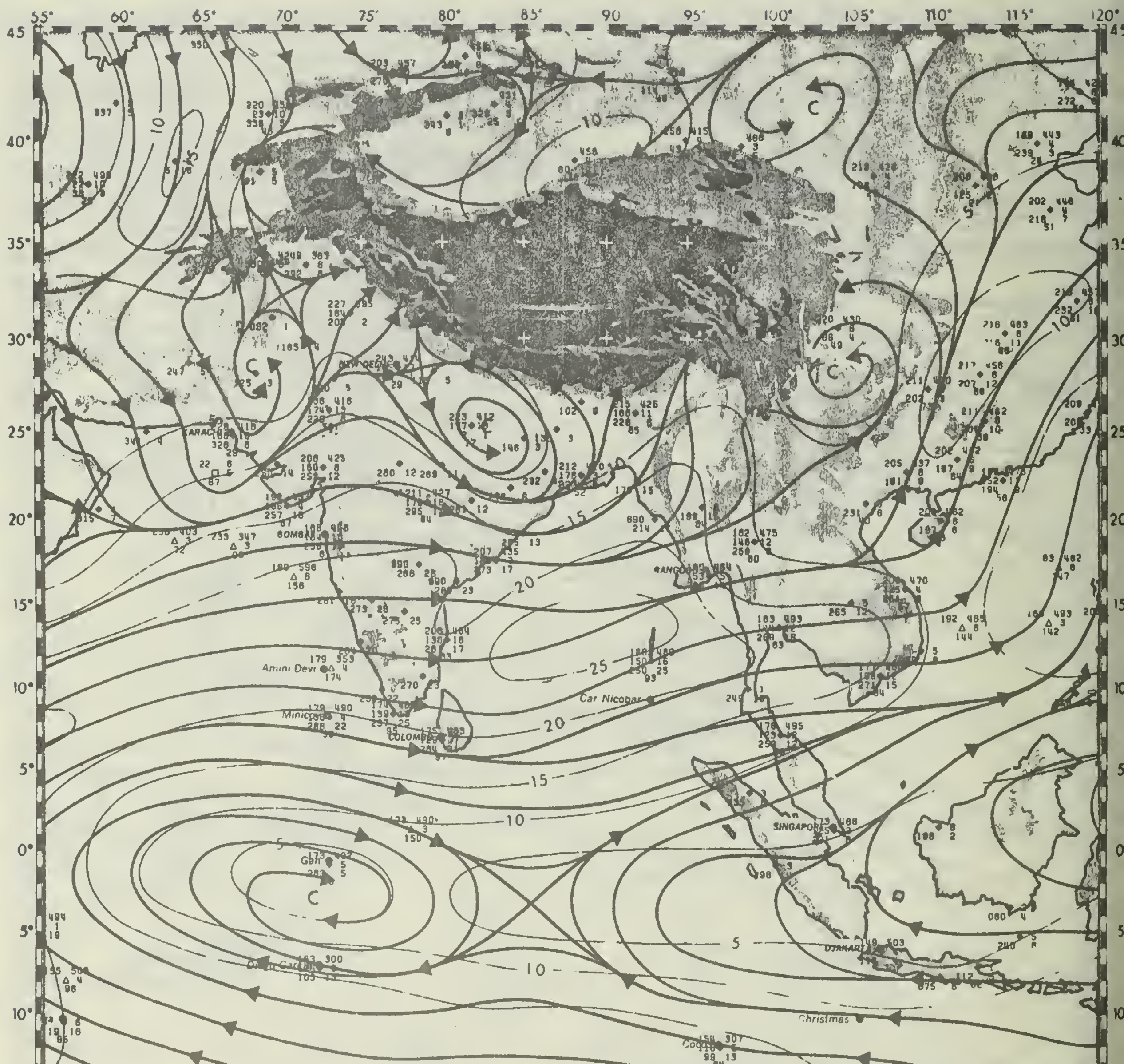


Figure B-5(a). 850 mb streamline chart (JUL).

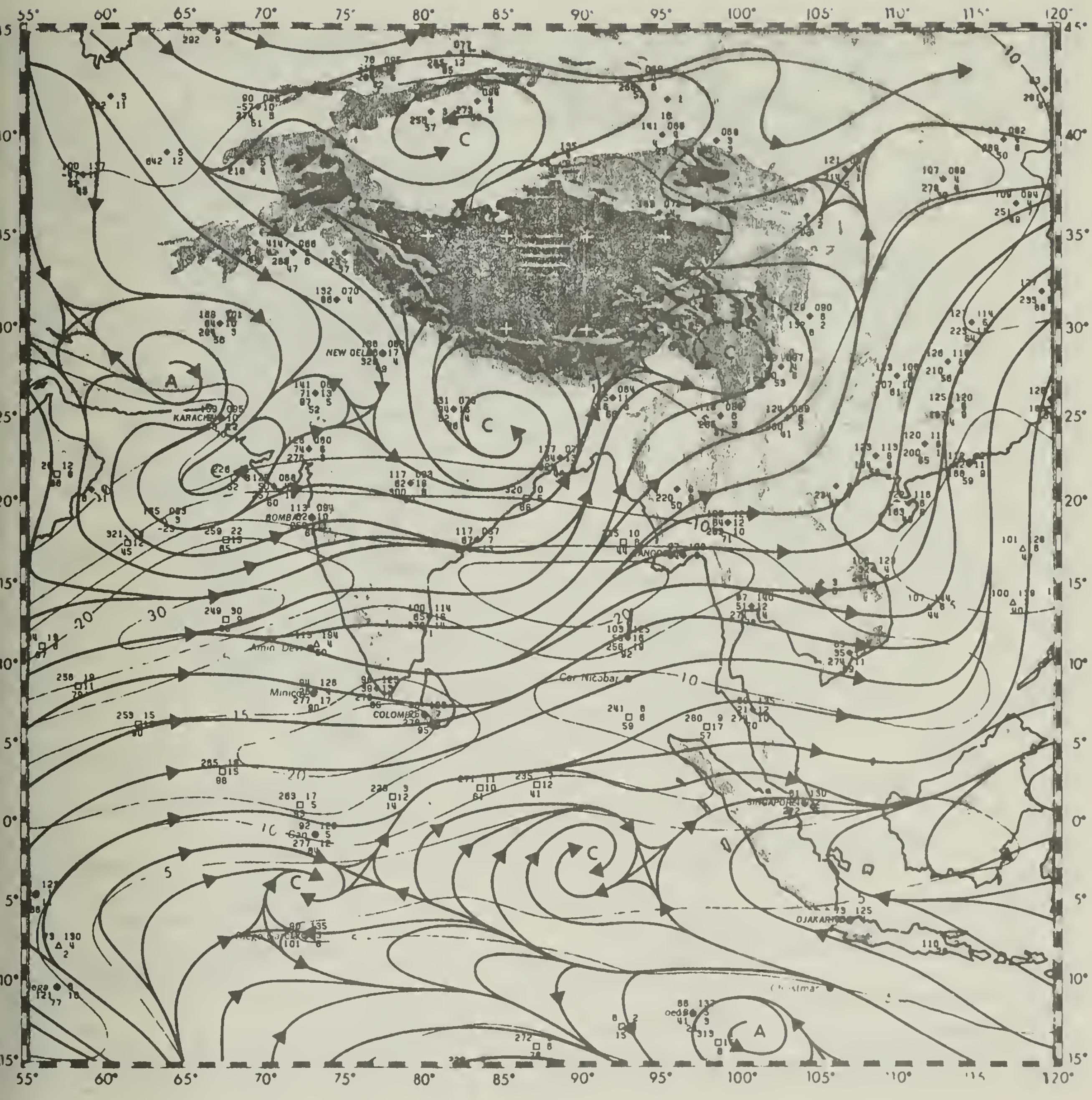


Figure B-5(b). 700 mb streamline chart (JUL).

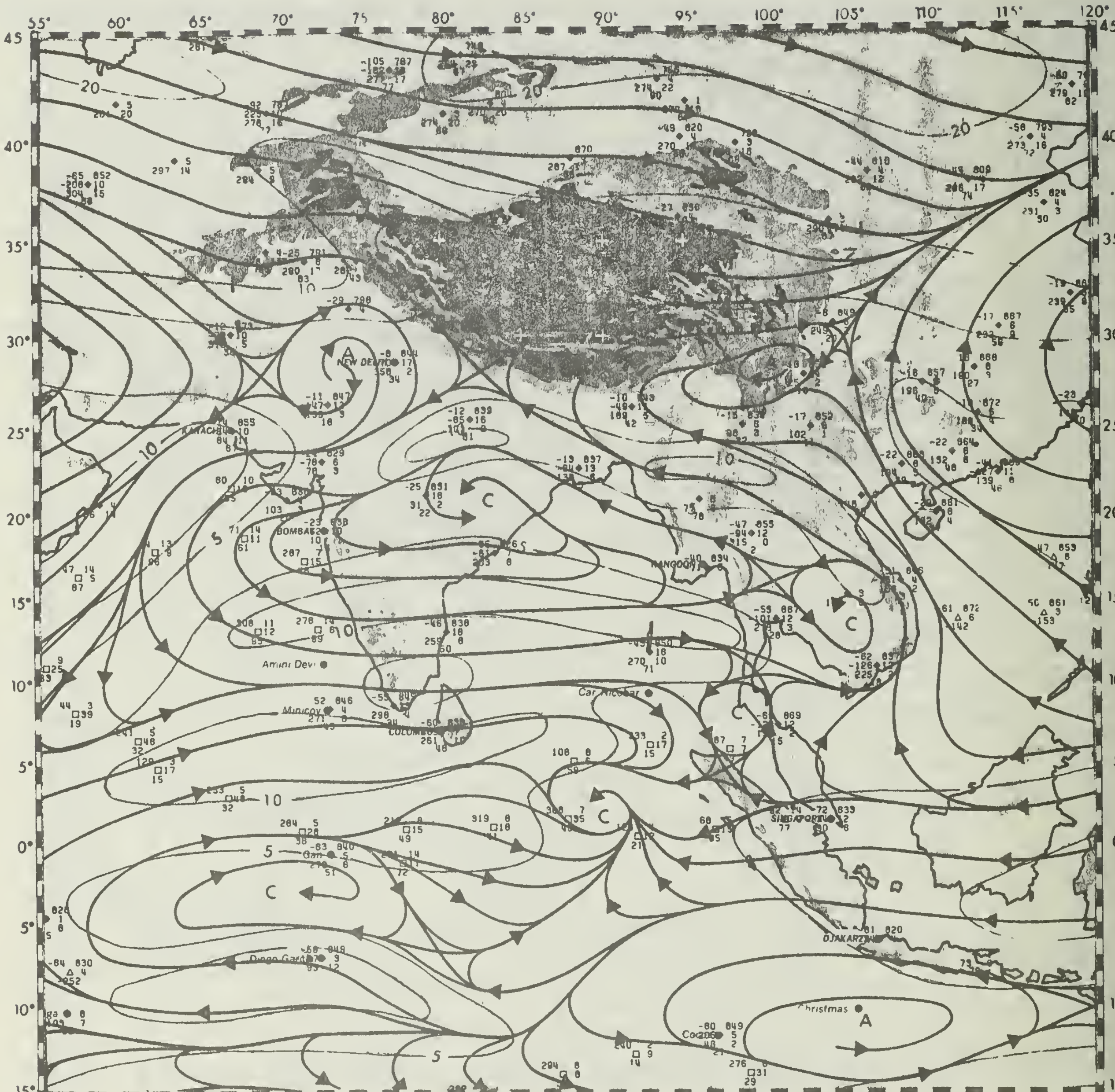


Figure B-5(c). 500 mb streamline chart (JUL).

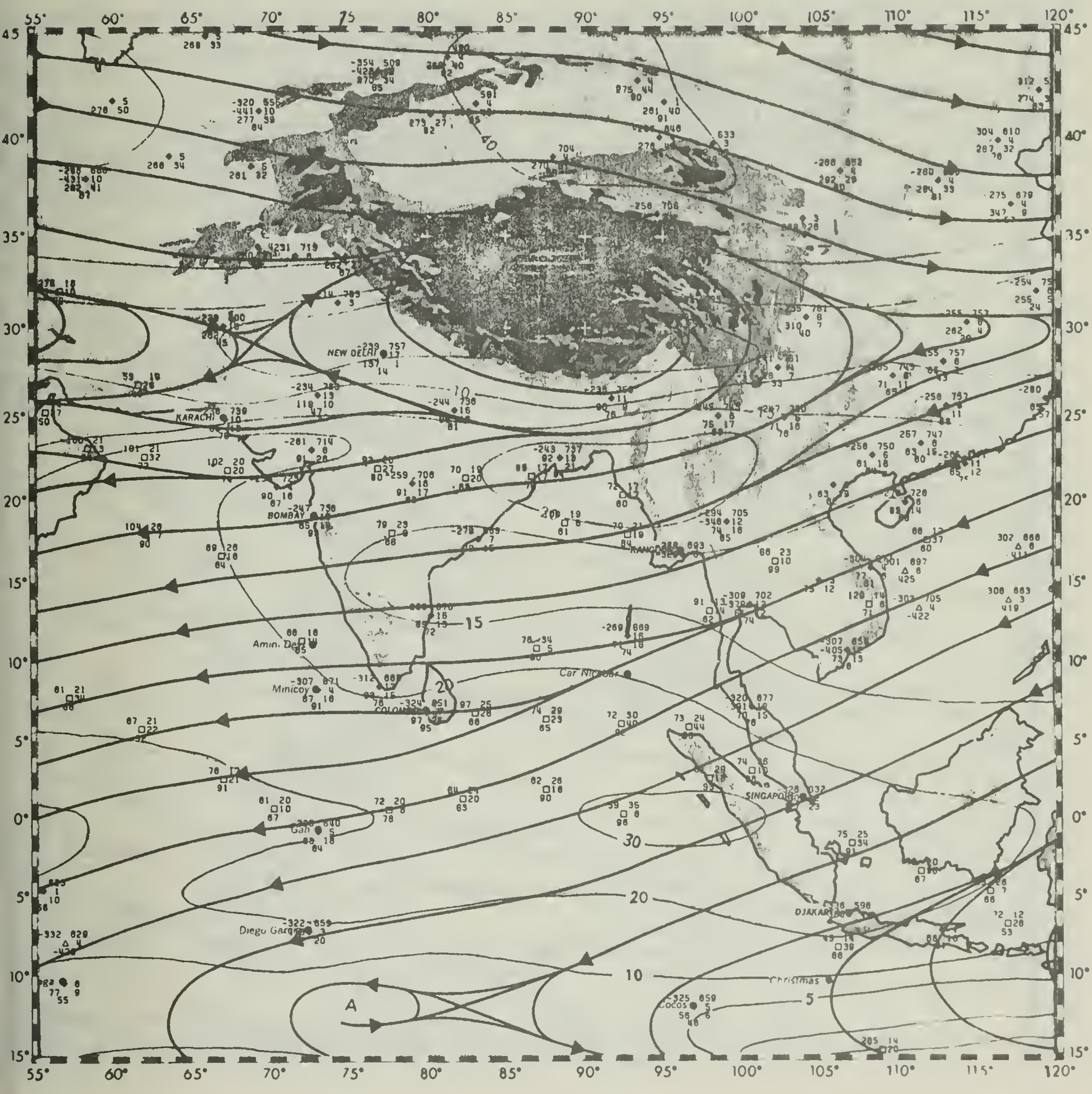


Figure B-5(d). 300 mb streamline chart (JUL).

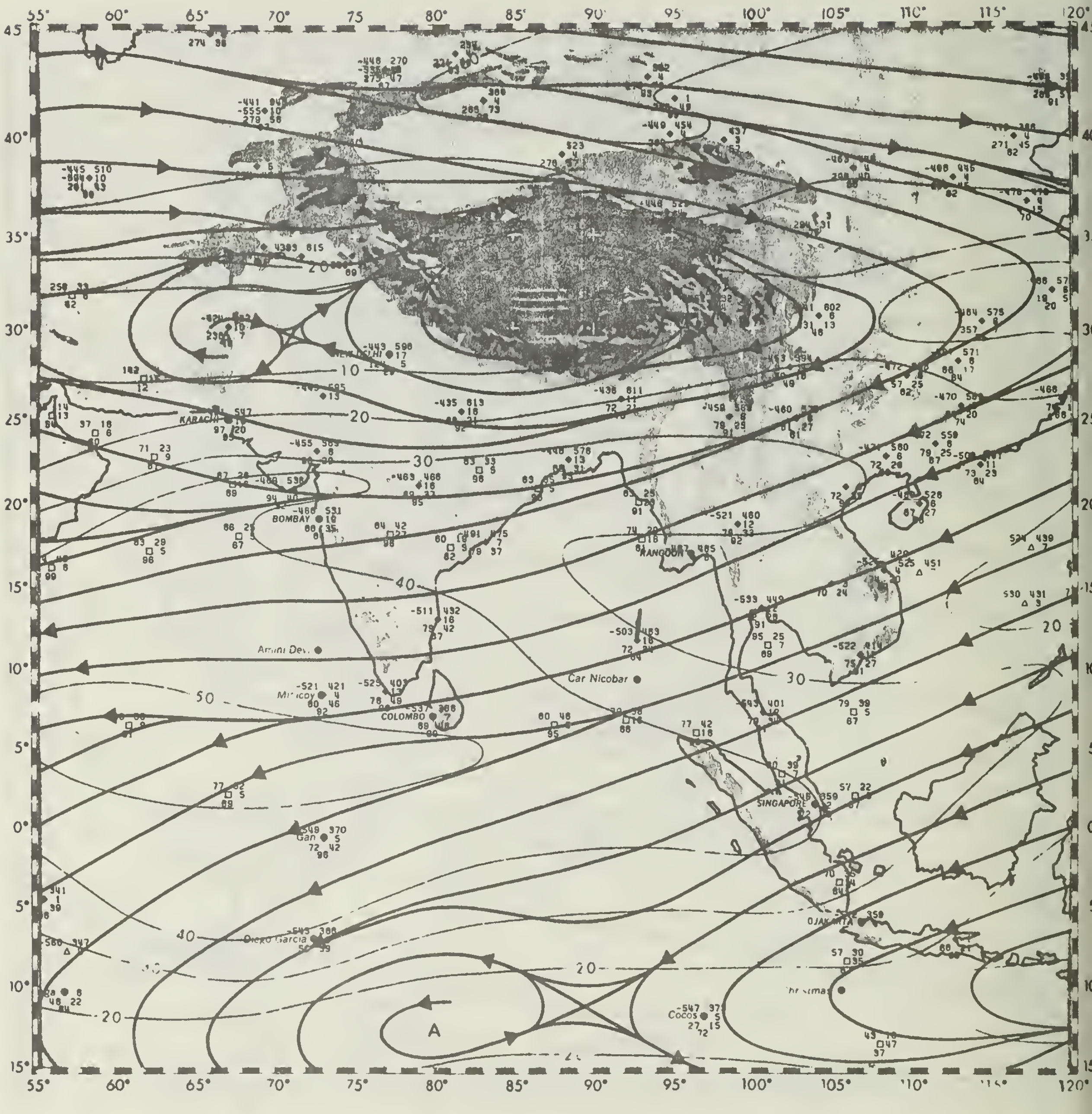


Figure B-5(e). 200 mb streamline chart (JUL).

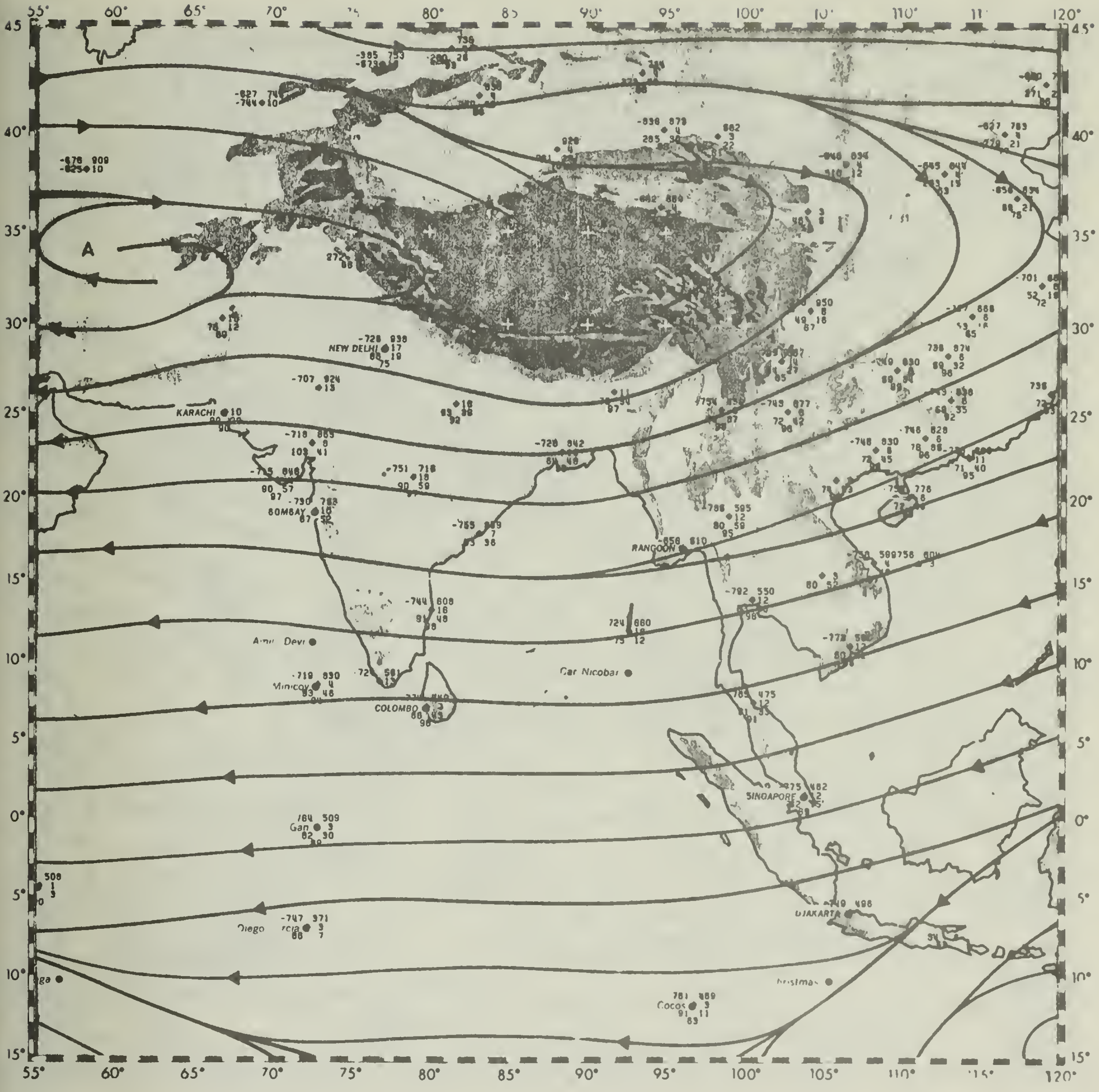


Figure B-5(f). 100 mb streamline chart (JUL).

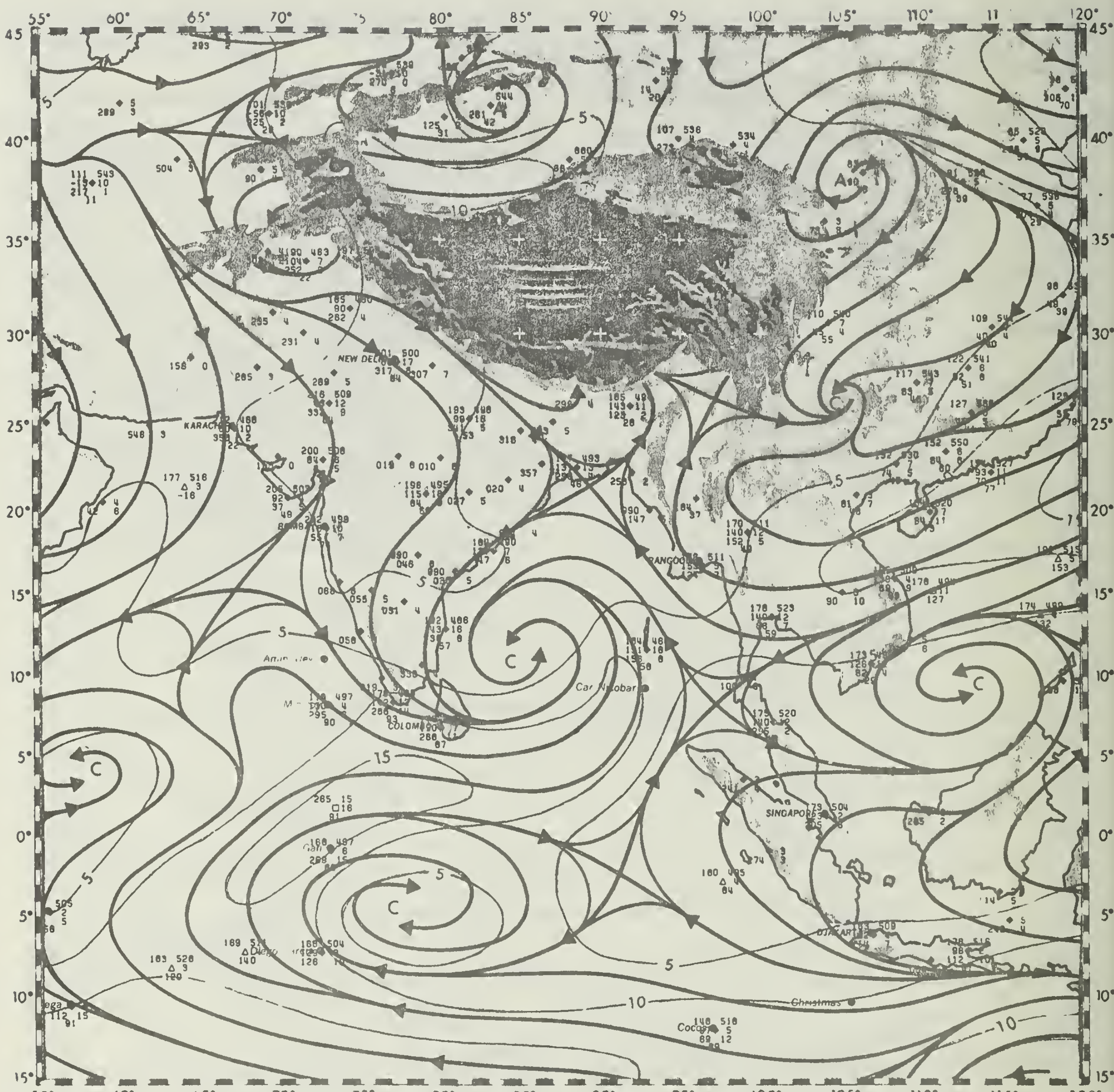


Figure B-6(a). 850 mb streamline chart (OCT).

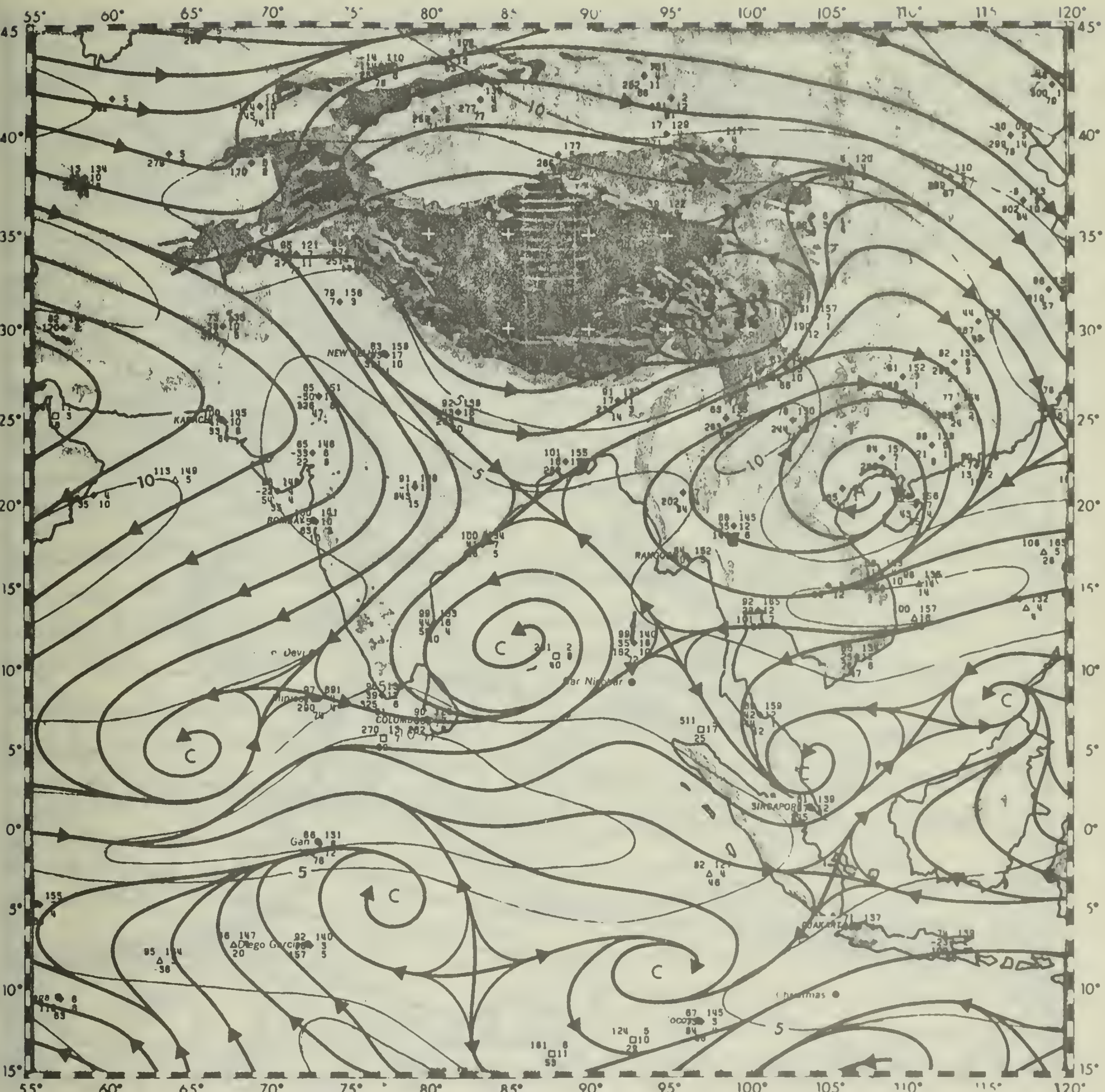


Figure B-6(b). 700 mb streamline chart (OCT).

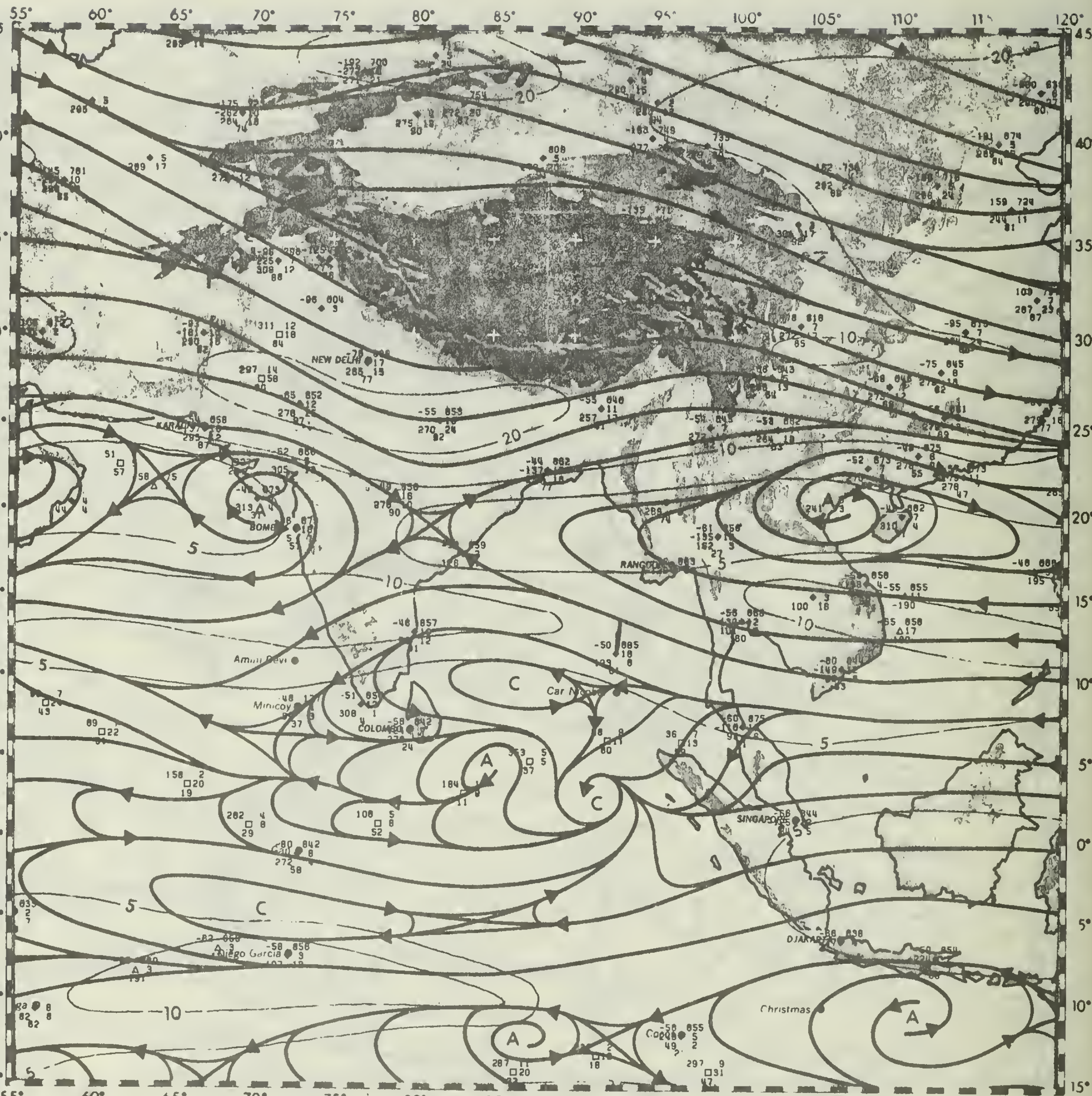


Figure B-6(c). 500 mb streamline chart (OCT).

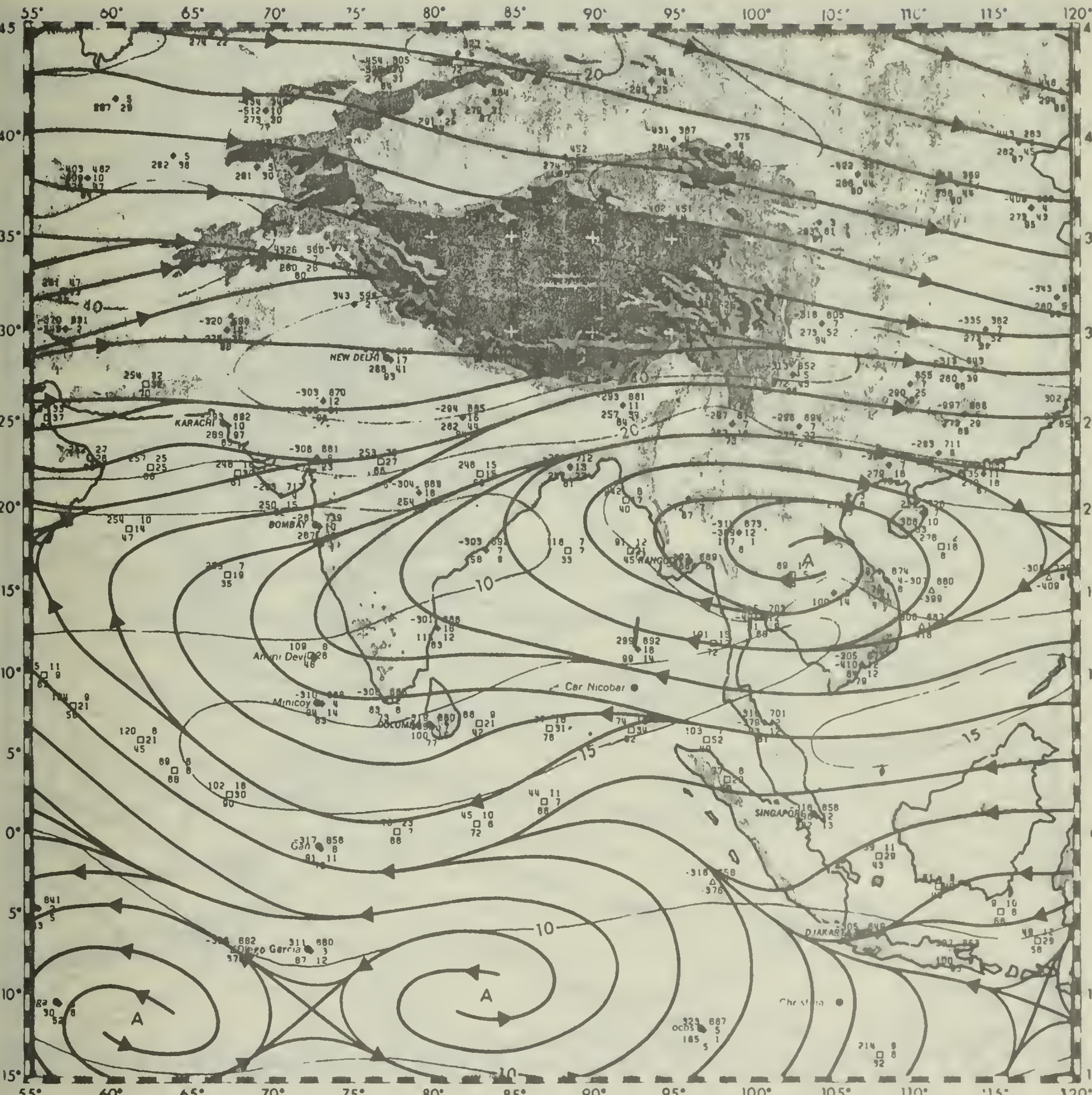


Figure B-6(d). 300 mb streamline chart (OCT).

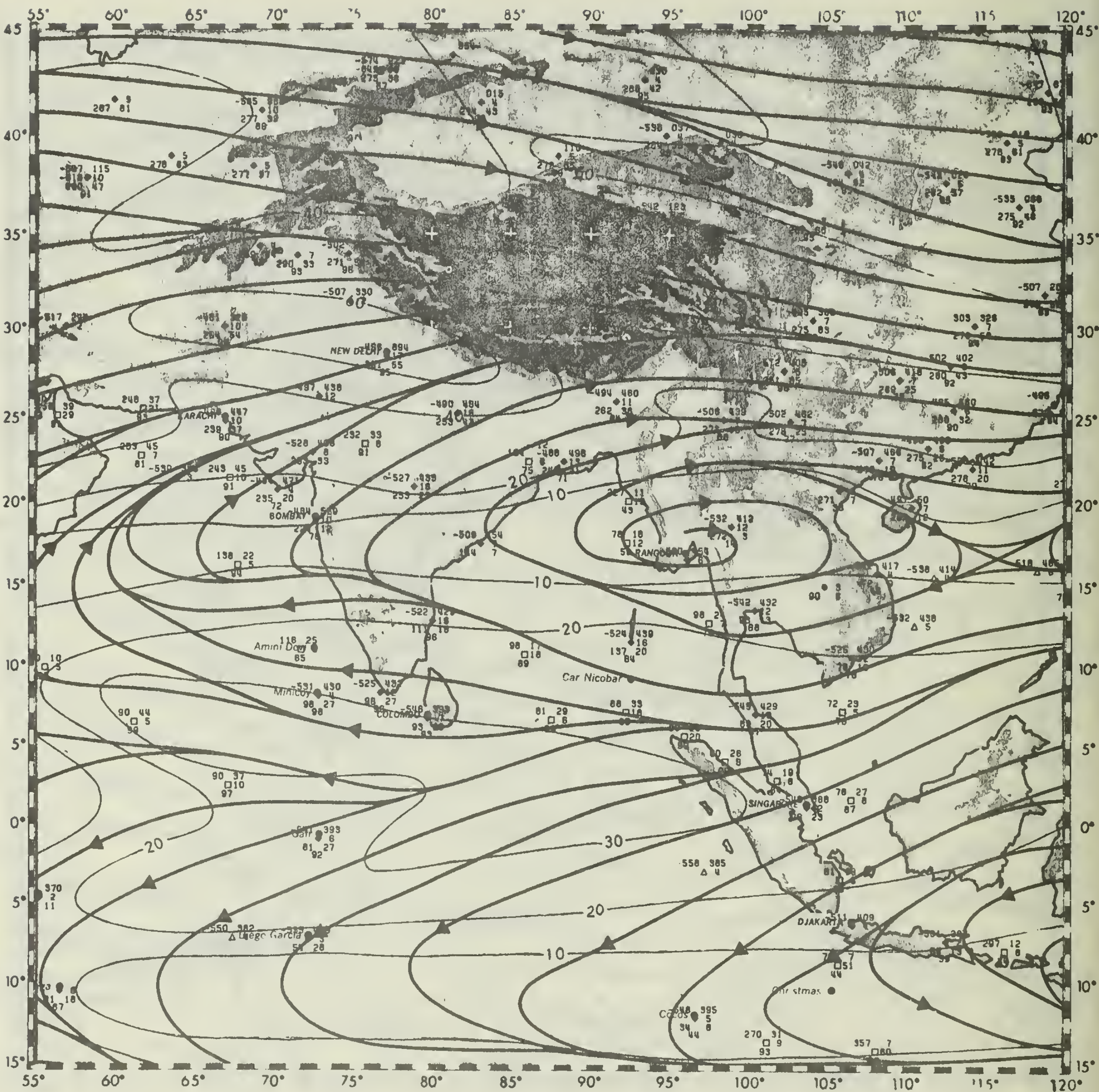


Figure B-6(e). 200 mb streamline chart (OCT).

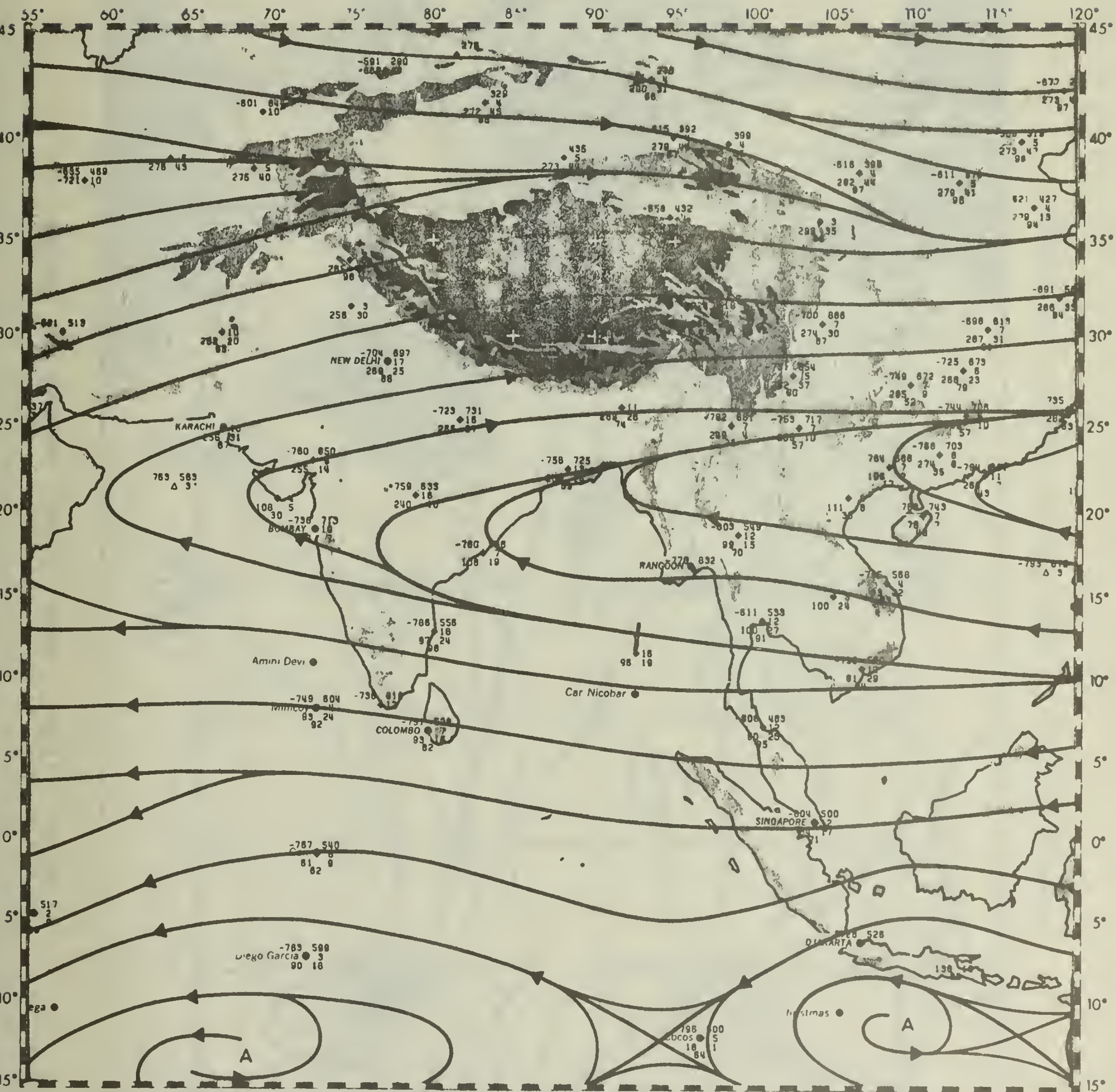
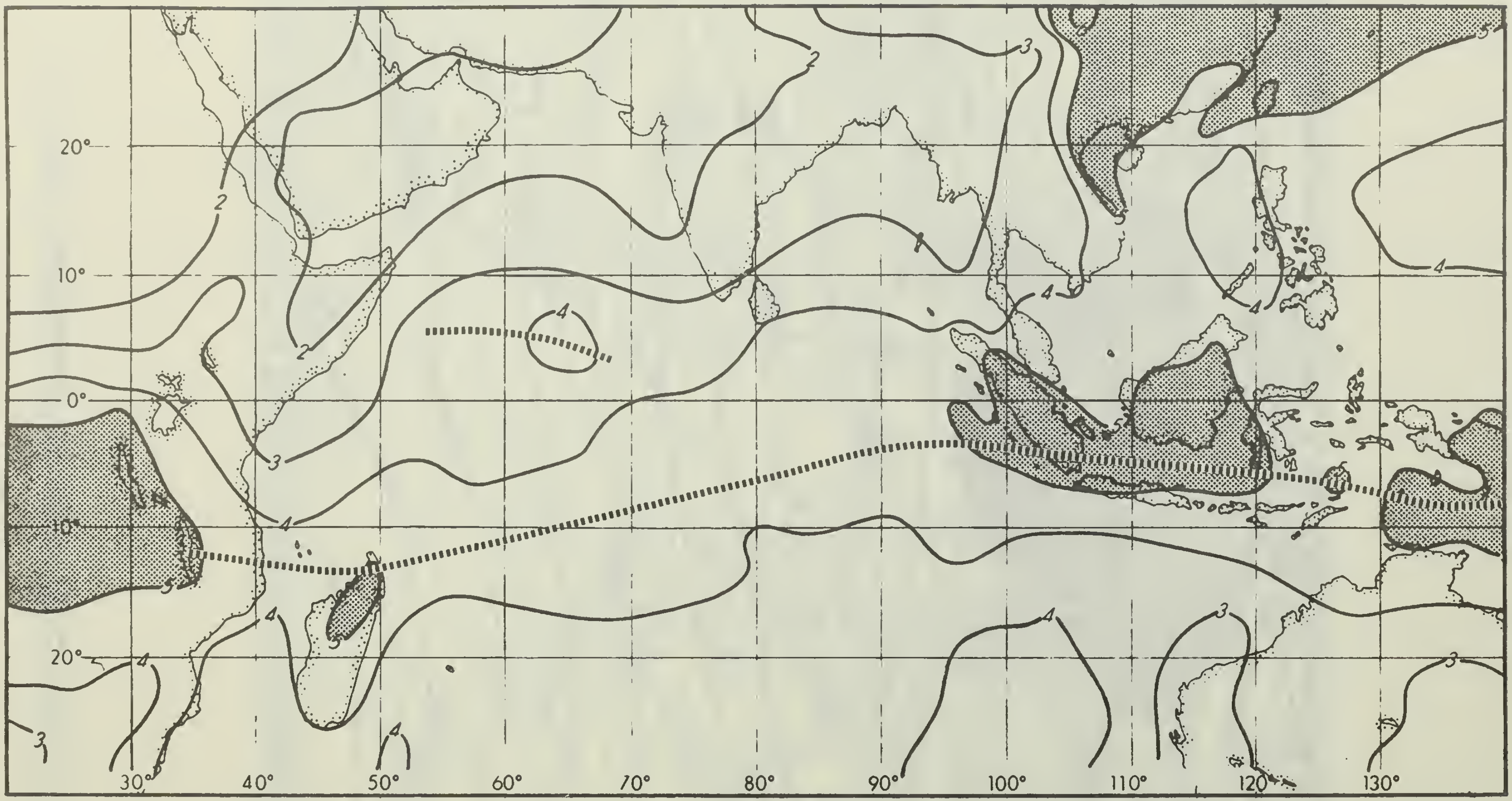


Figure B-6(f). 100 mb streamline chart (OCT).



JAN

Figure B-7(a). Mean cloud amount in Oktas.

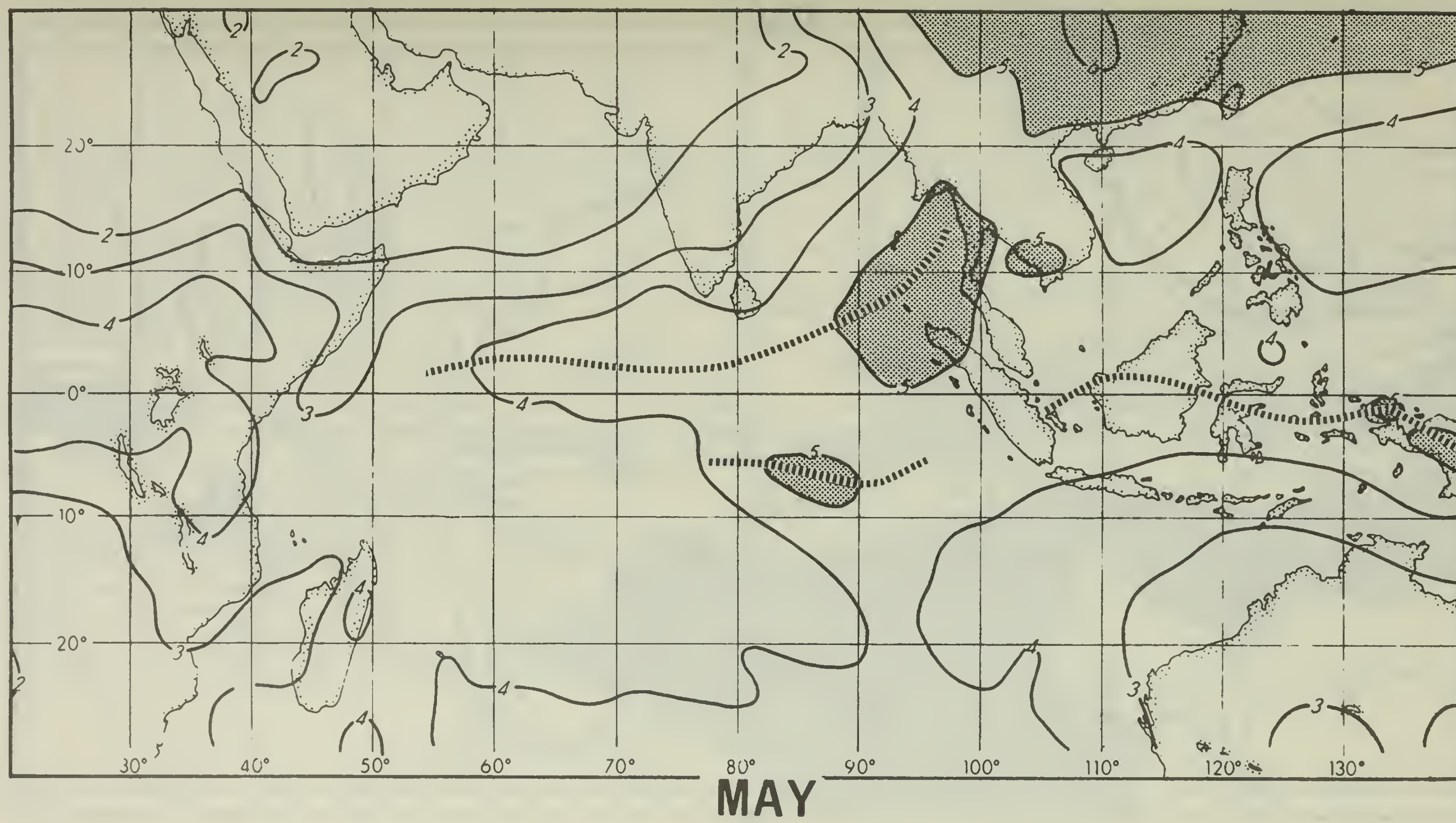


Figure B-7(b). Mean cloud amount in Oktas.

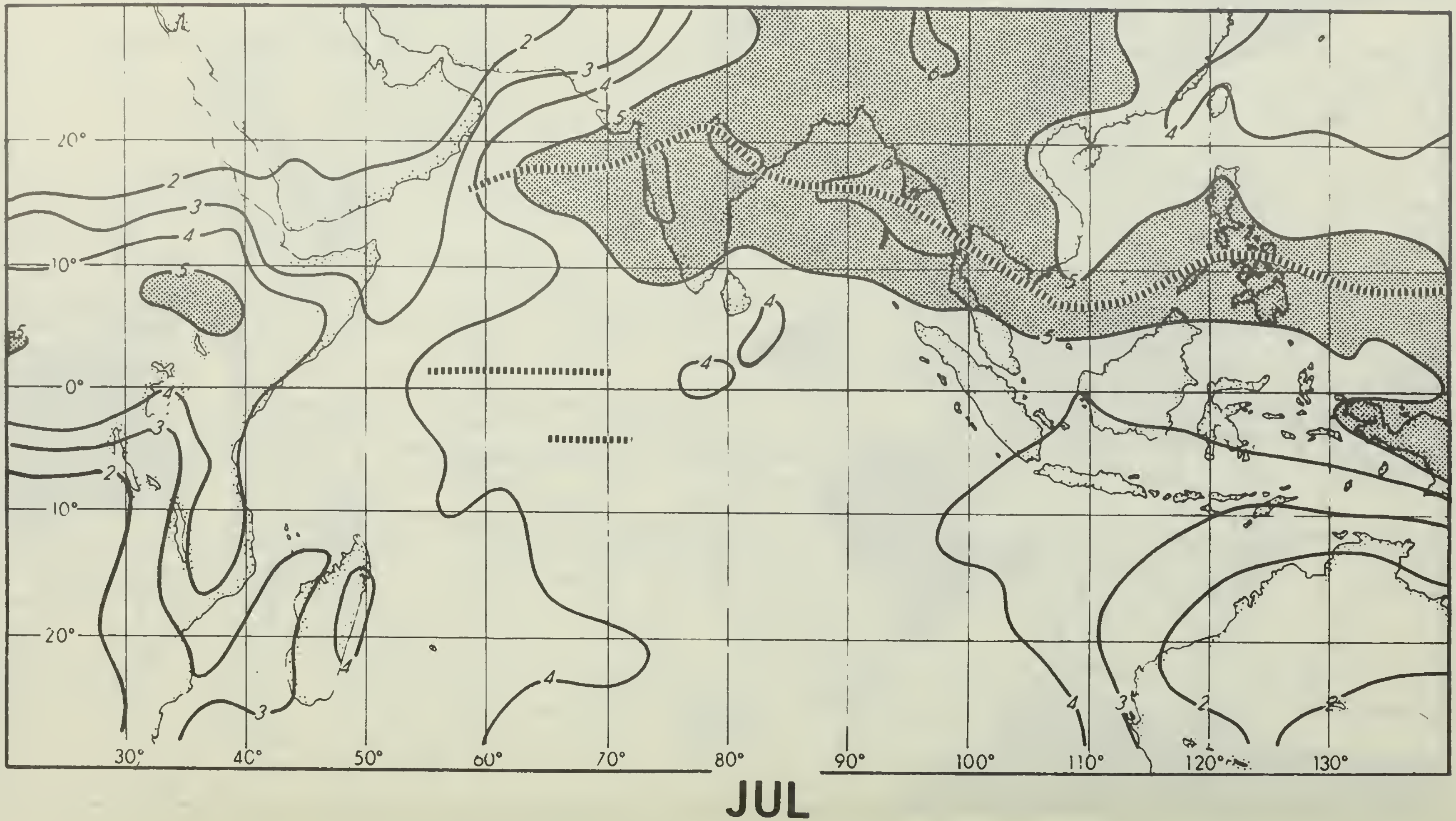


Figure B-7(c). Mean cloud amount in Oktas.

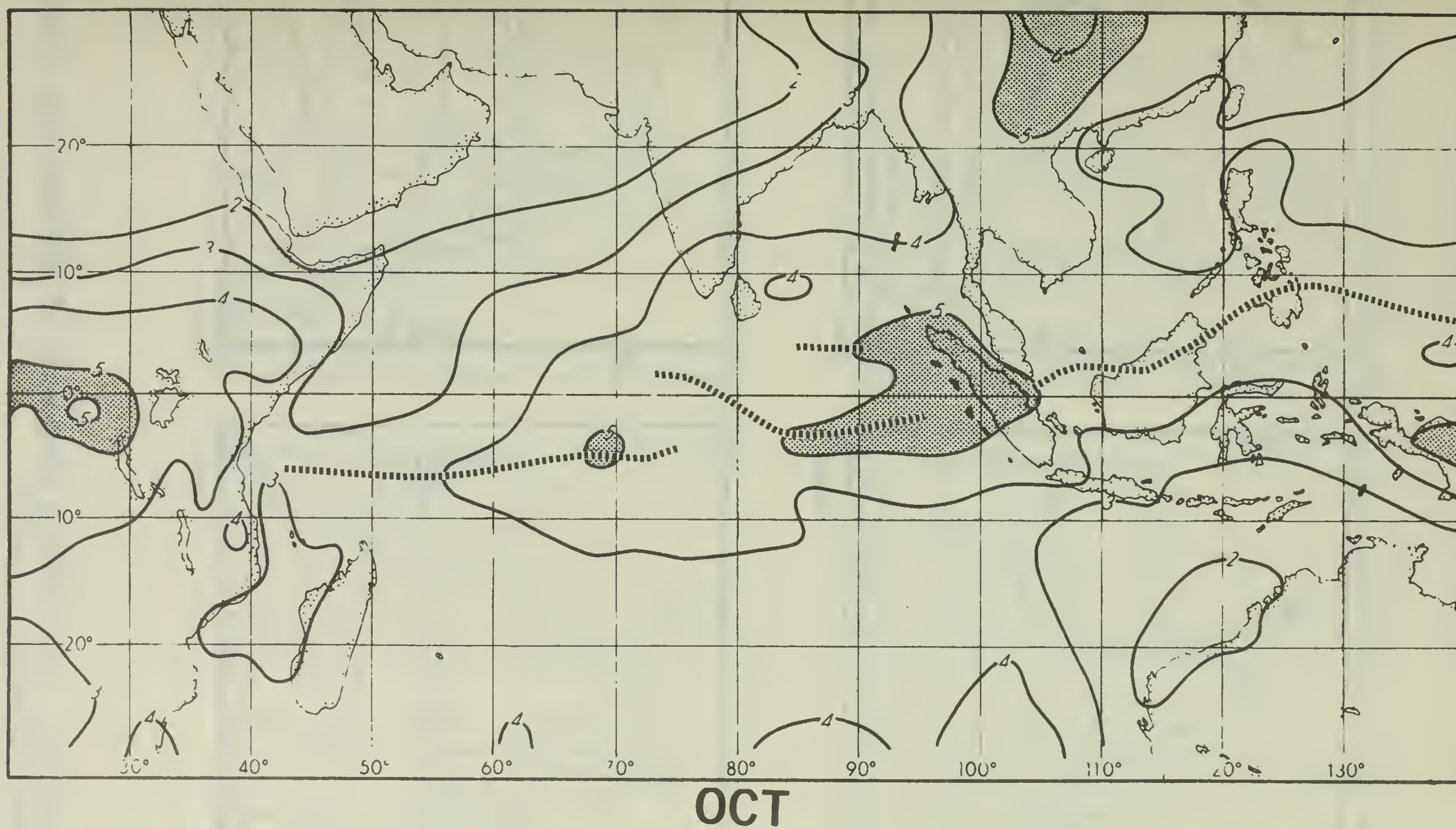


Figure B-7(d). Mean cloud amount in Oktas.

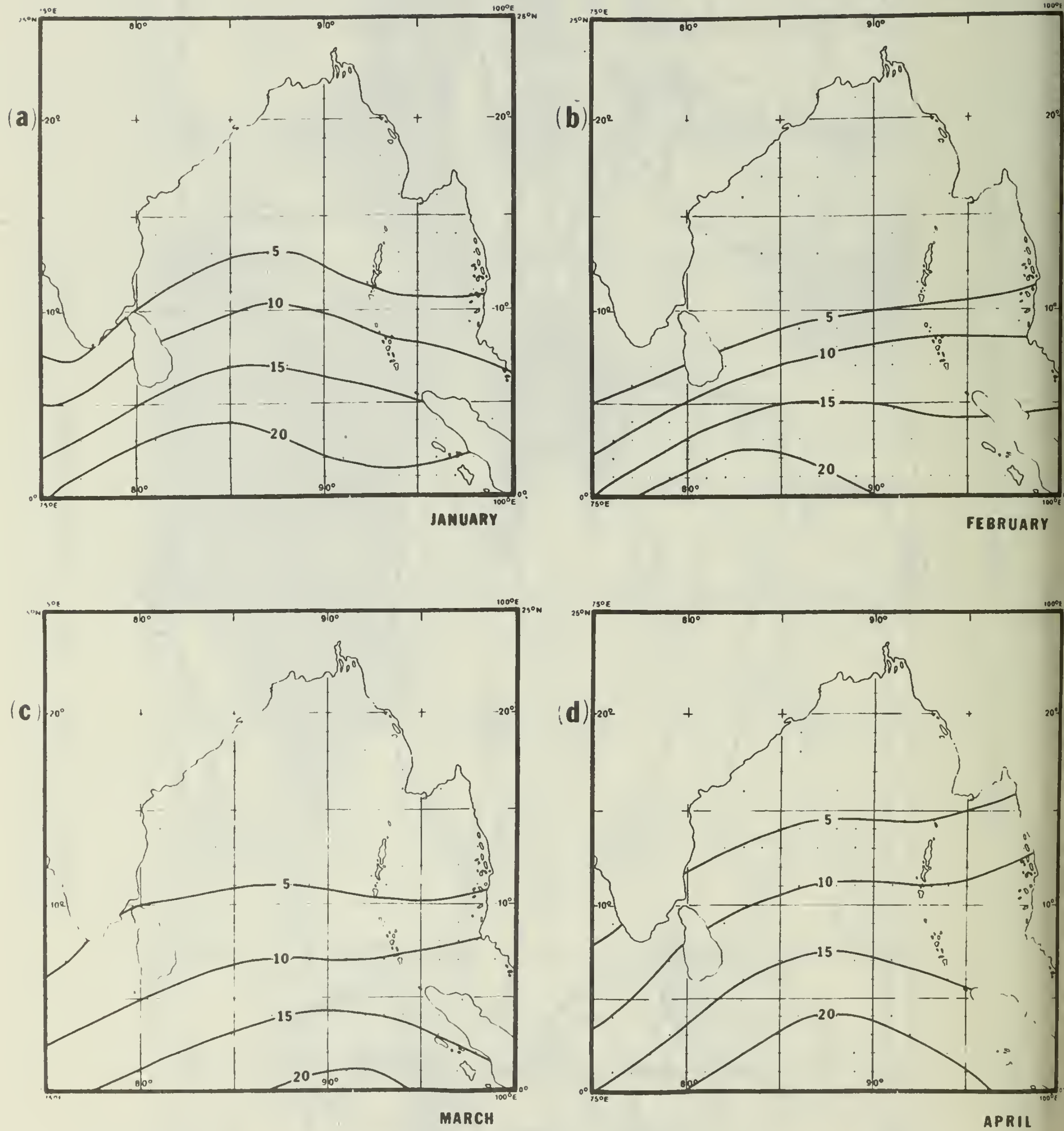


Figure B-8. Percentage frequency of observations reporting precipitation (by month).

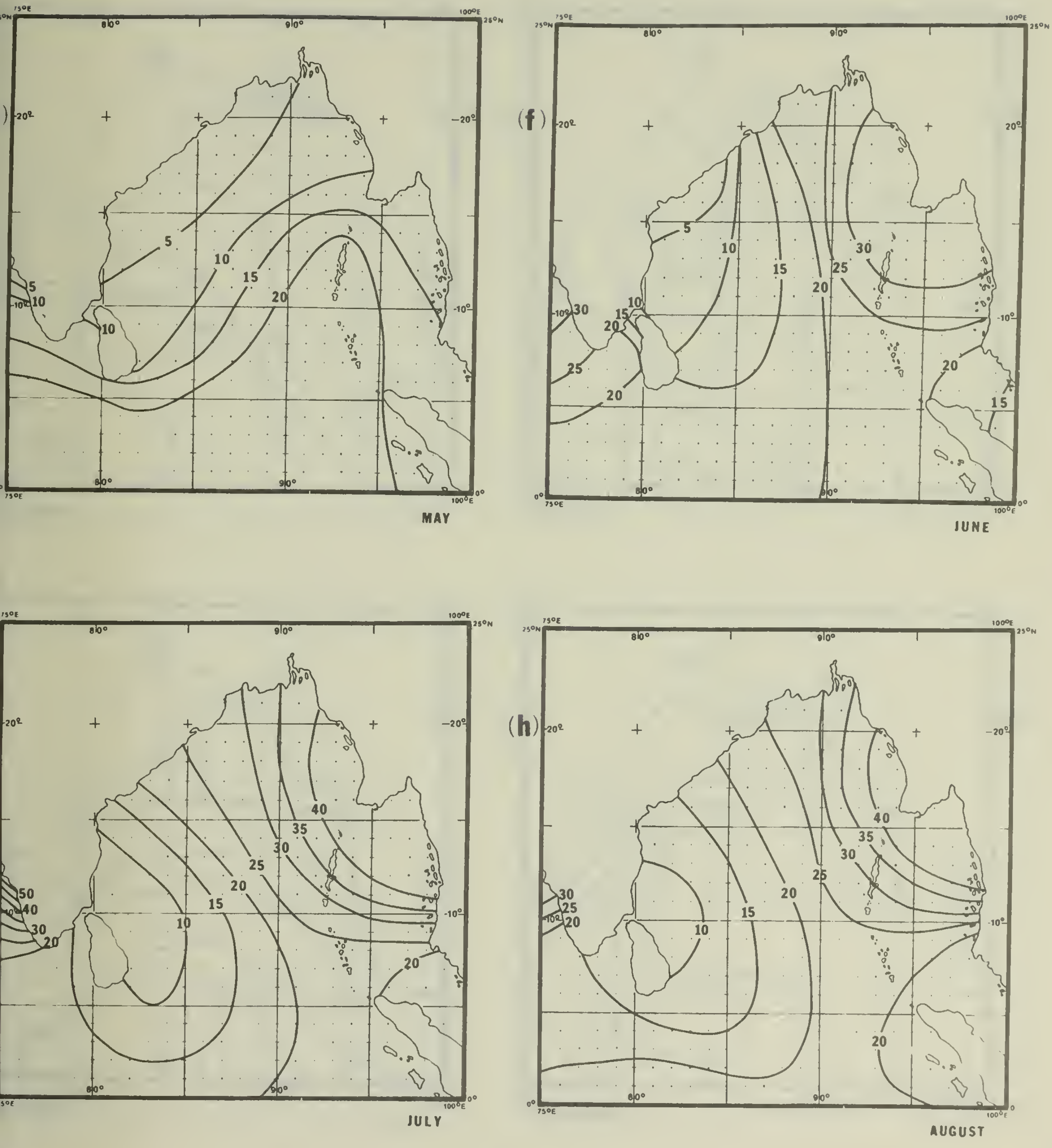


Figure B-8. (Continued)

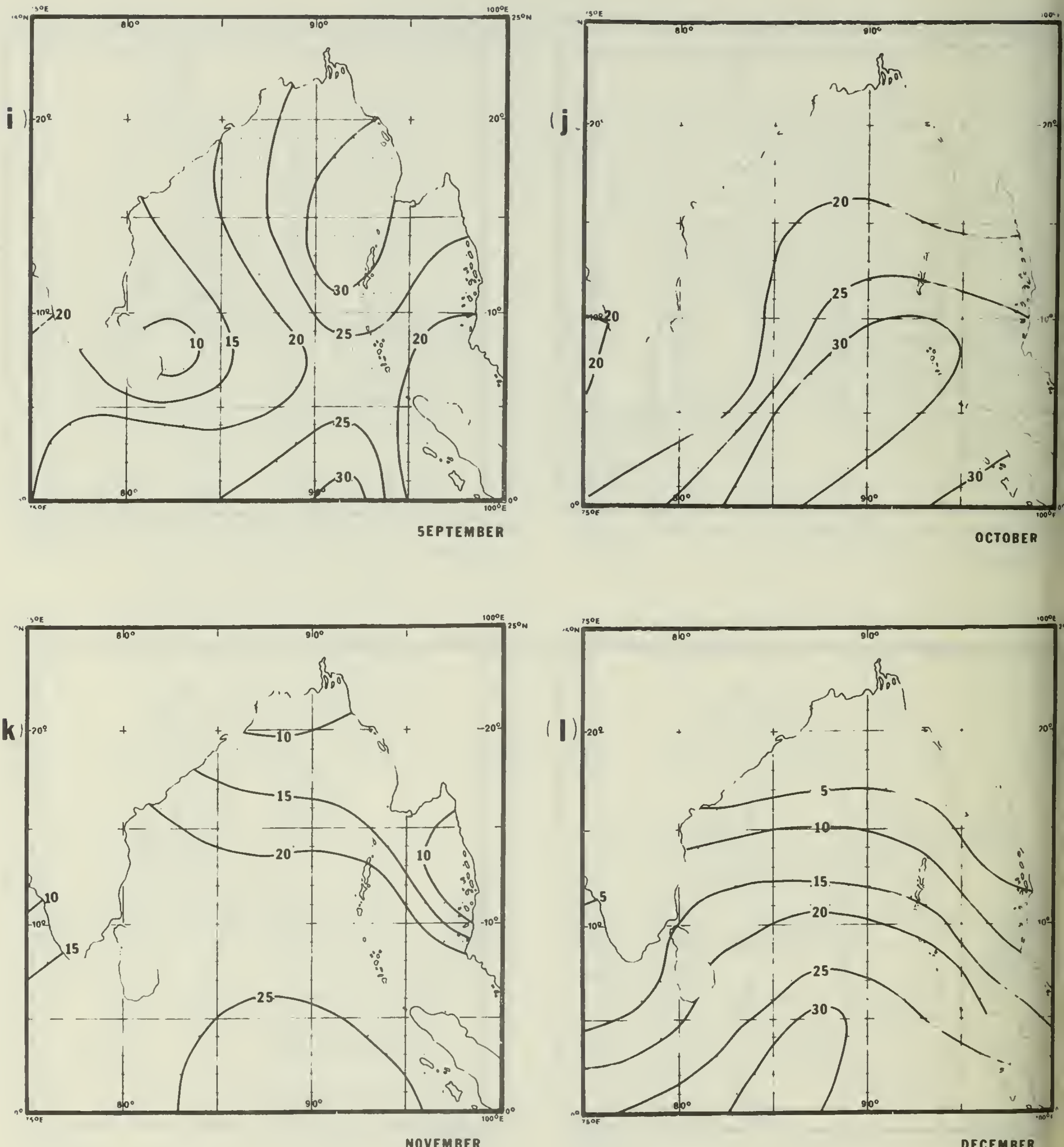


Figure B-8. (Continued)

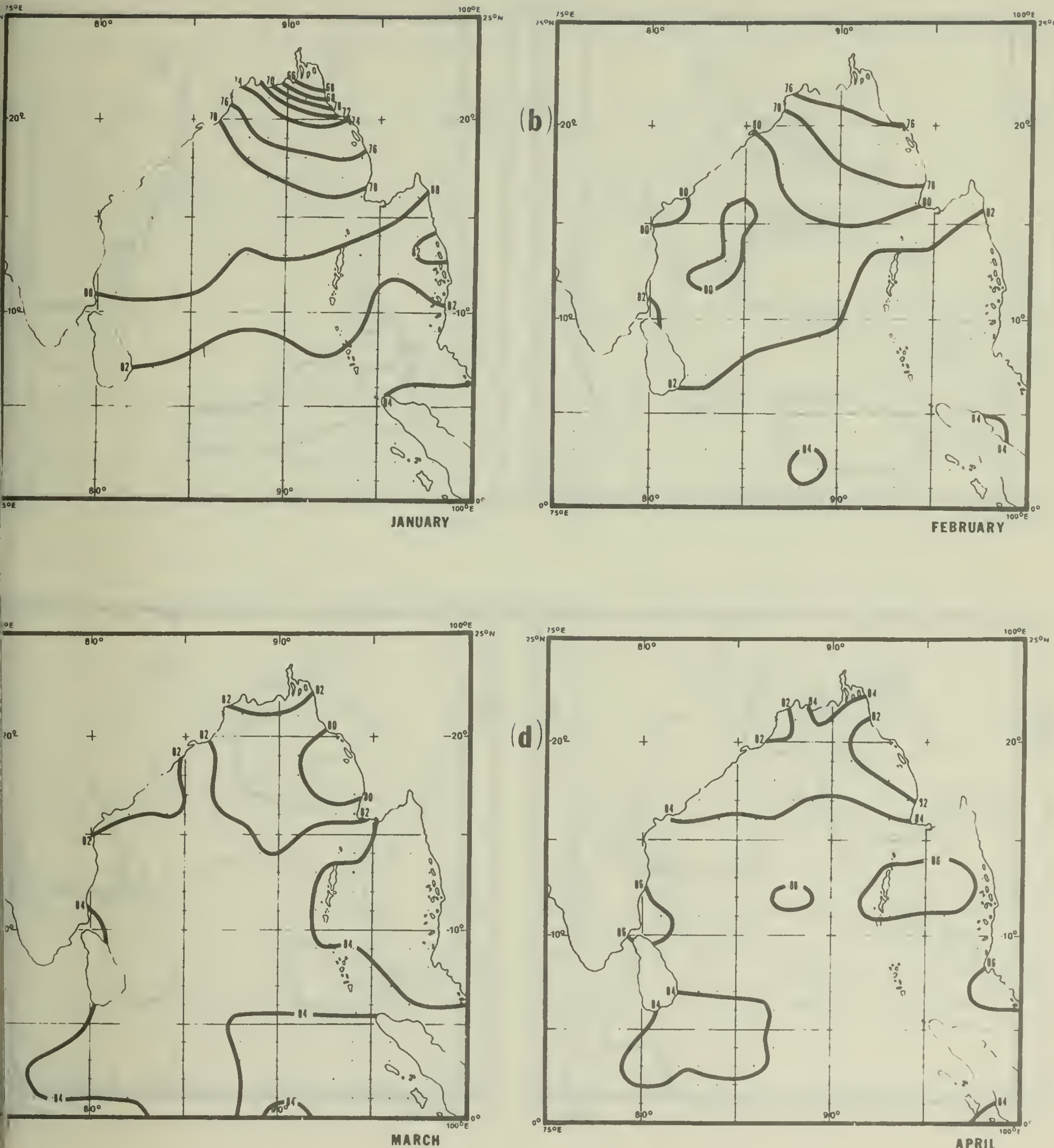


Figure B-9. Sea-surface temperature (by month).

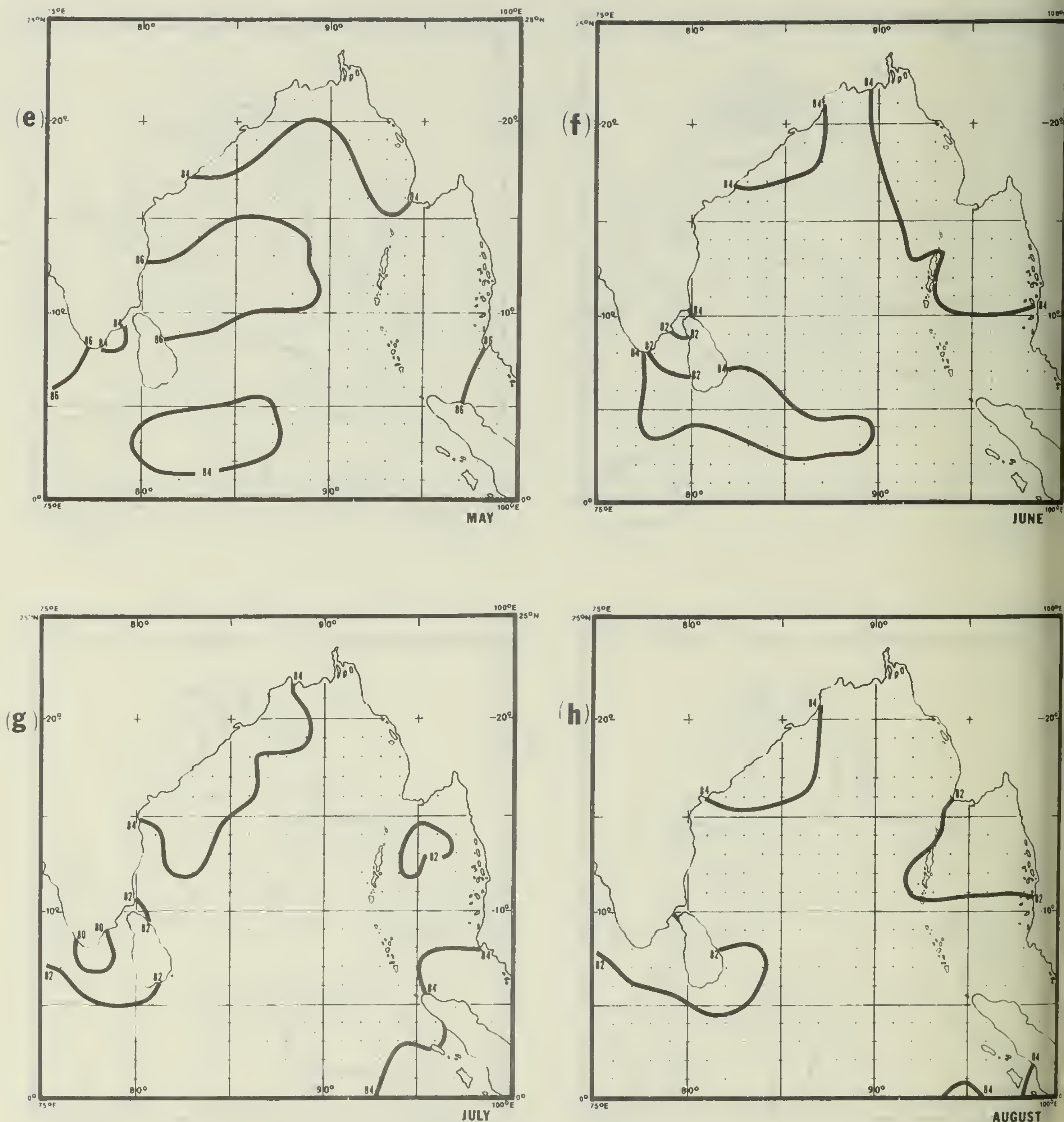


Figure B-9. (Continued).

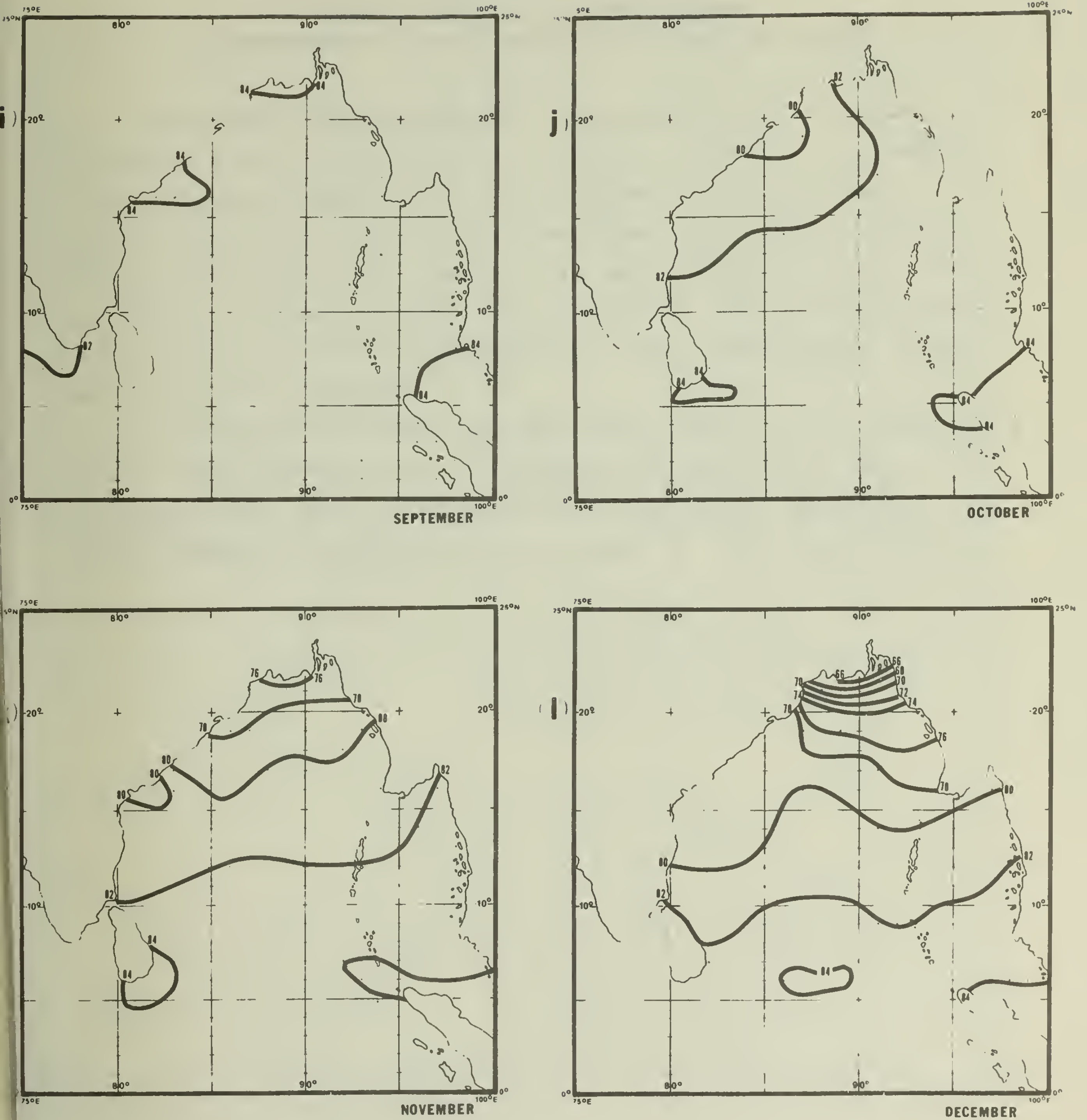


Figure B-9. (Continued).

APPENDIX C

SAMPLE SATELLITE PHOTOGRAPHS ILLUSTRATING CONDITIONS IN THE BAY OF BENGAL

The satellite photographs contained in this section have not been chosen to show "normal" conditions. Rather, they are presented to illustrate some of the phenomena discussed in the body of the text and references to these photographs have been made in the appropriate places. This appendix contains a brief description of the salient points brought out by each photograph and cross-references to the main text are provided.

It should be noted that the date given is the "satellite date." The actual date in the area of the Bay of Bengal is one day later; e.g., the satellite photograph dated Feb. 2, 1970 (Figure C-1) corresponds to Feb. 3, 1970 over the bay.

Figure C-1 (opposite)
Digitized ESSA-9 satellite photograph dated February 2, 1970

Features

This is a typical winter picture with no dangerous meteorological features in the Bay of Bengal. The cloud mass near 35N 65E is a western disturbance of the "amorphous cloud area" (see paragraph 4.7). The Southern Hemisphere Convergence Zone is well-developed, lying between 5S and 10S; note the latitudinal extent of the intense convective activity and see paragraph 4.2.4. Also note the convective activity between 5N and 10N from 75E to 90E; this is the Northern Hemisphere Convergence Zone. In practice this cloud mass should be kept under observation in order to detect any northerly movement (paragraph 6.2.1). Over the bay, conditions are generally clear, with cloud amounts increasing to the south (paragraph 6.2.1). Note the convective activity over the Eastern Ghats and also the southern hemisphere tropical storm (around 18S, 78E).

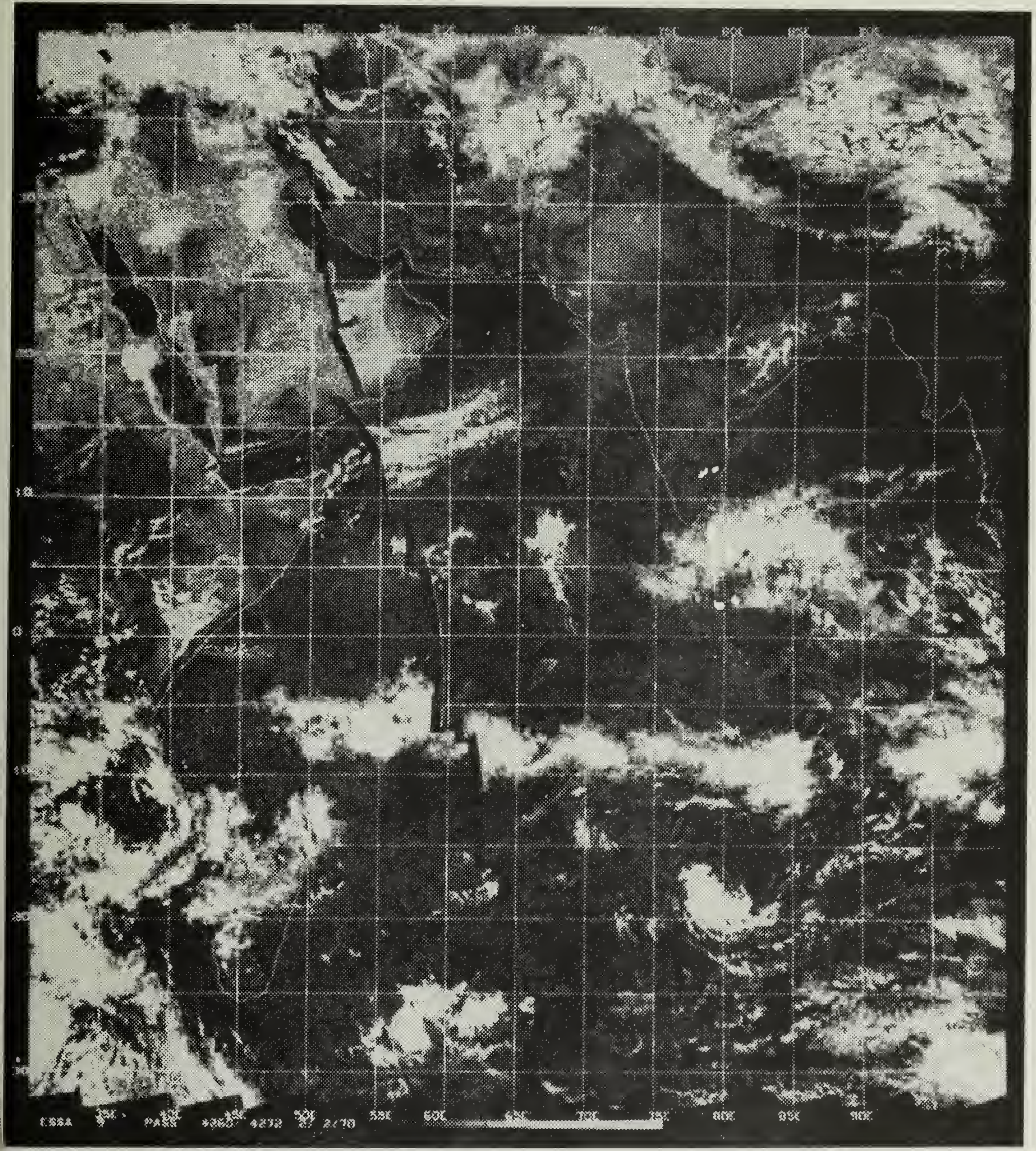


Figure C-1

Figure C-2 (opposite)
Digitized ESSA-9 satellite photograph dated May 23, 1970

Features

This was taken during the spring transition season. (See paragraph 6.2.2). Note the increase in convective activity over India compared with Figure C-1. Later in the day, these cells may move out over the water to cause "Nor'westers" (paragraphs 4.6 and 6.2.2).

Squalls and showers already affect the northeastern part of the Bay of Bengal. The cloud mass near 12N, 87E should be kept under observation for possible development. This is a typical picture for spring.

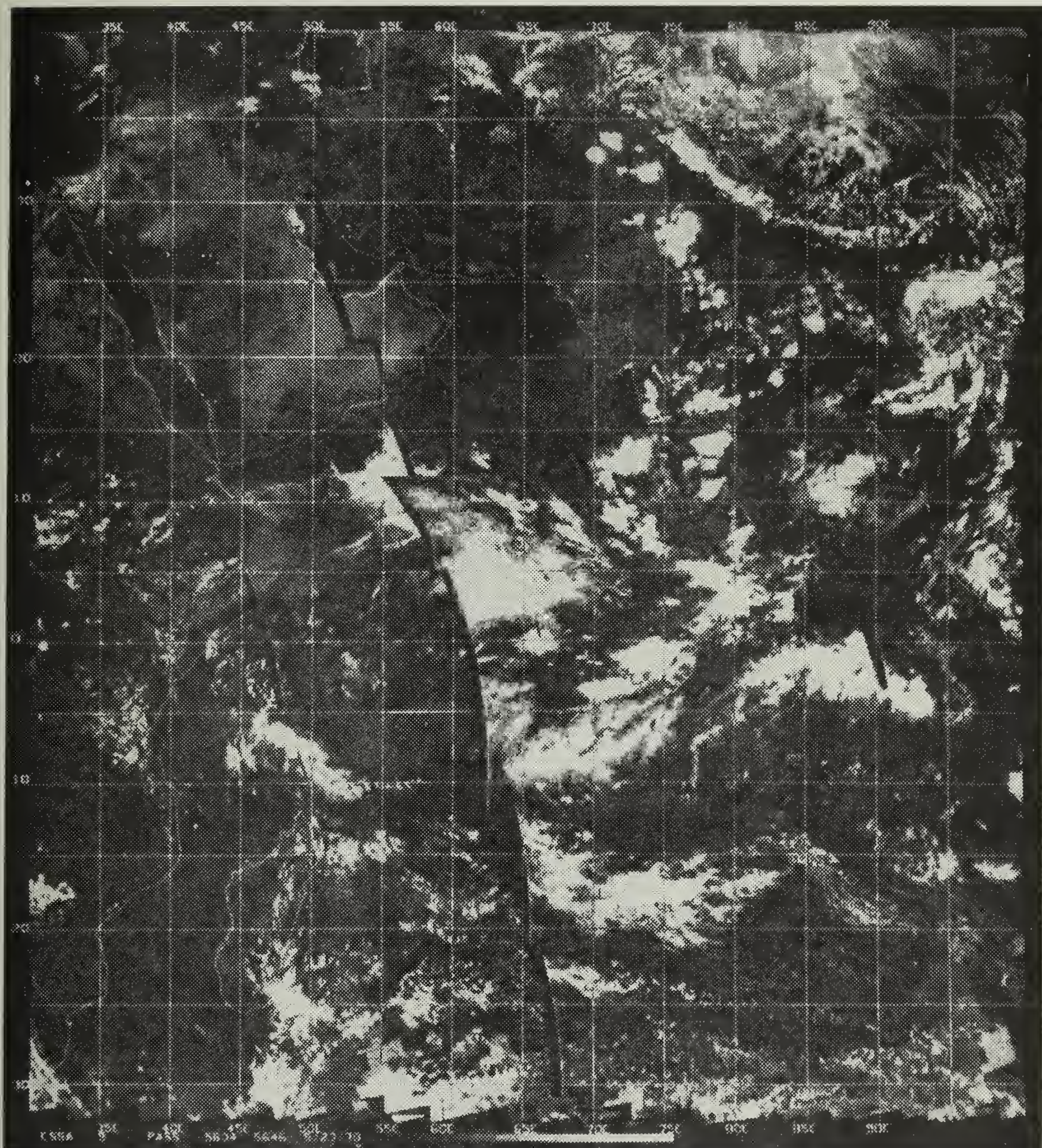


Figure C-2

Figure C-3 (opposite)
Digitized ITOS-1 satellite photograph dated May 2, 1970

Features

This was taken 3 weeks before Figure C-2 with which it should be compared. The Southern Hemisphere Convergence Zone is better defined but the main feature is, of course, the well-developed cyclonic storm over the Bay of Bengal. Subsidence around the storm is clearly shown by the lack of clouds. Apart from the intense convective activity near the center and in the main feeder band extending southwest to the south of India, note the intense showers/squalls in the eastern part of the bay.

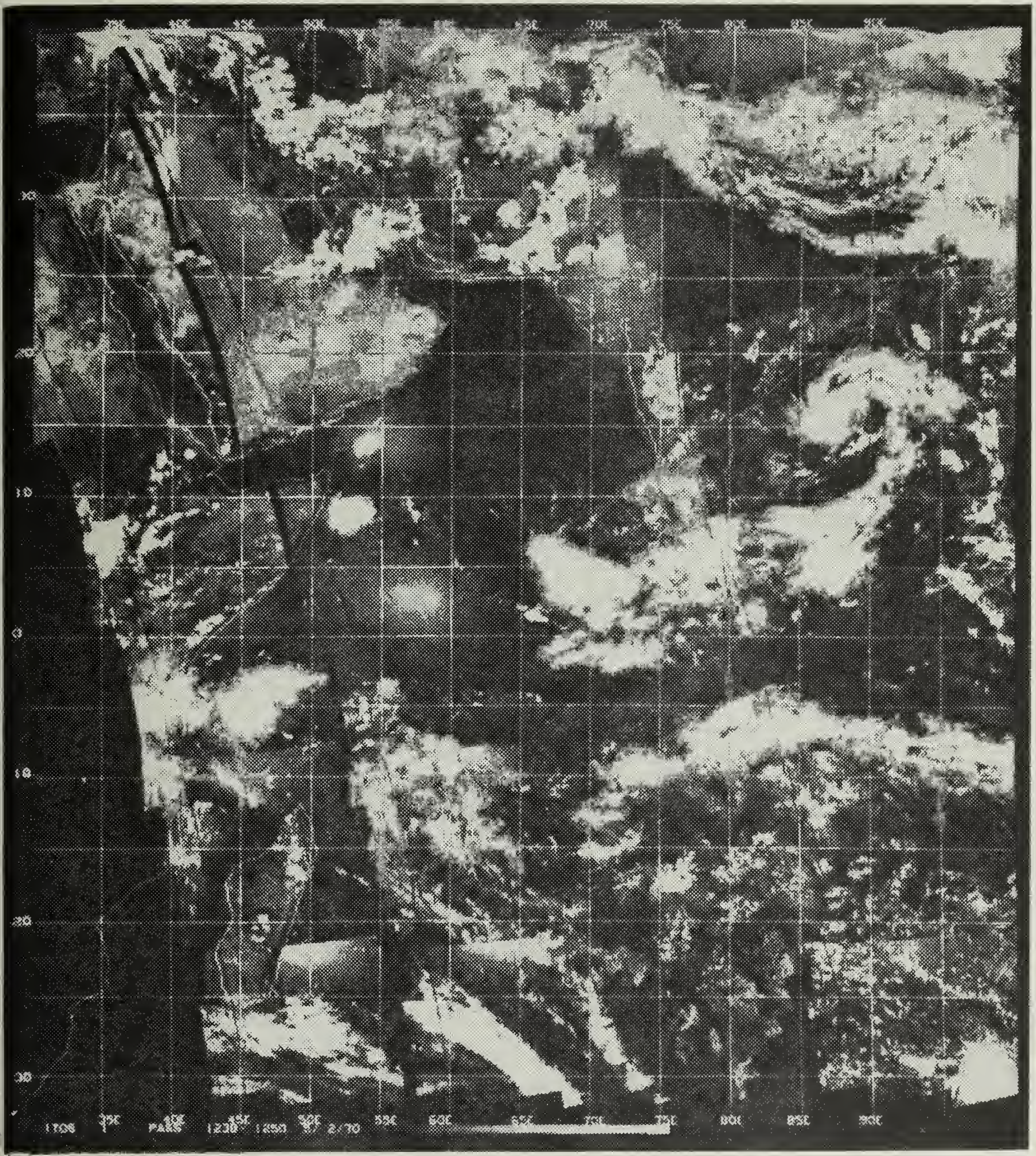


Figure C-3

Figure C-4 (opposite)
Digitized ESSA-9 satellite photograph dated July 29, 1969

Features

This was taken during the southwest monsoon season. Prior to the time of the photograph, a monsoon depression formed over the Bay of Bengal and moved into northeast India. In the photograph, the center is located near the coast at about 21N 87E. Note how difficult it is to locate the center. The major precipitation region is to the southwest of the center (see paragraph 4.3.2). Also note the hard echoes to the north (paragraph 4.3.2). An intense monsoon depression is shown in Figure C-5.

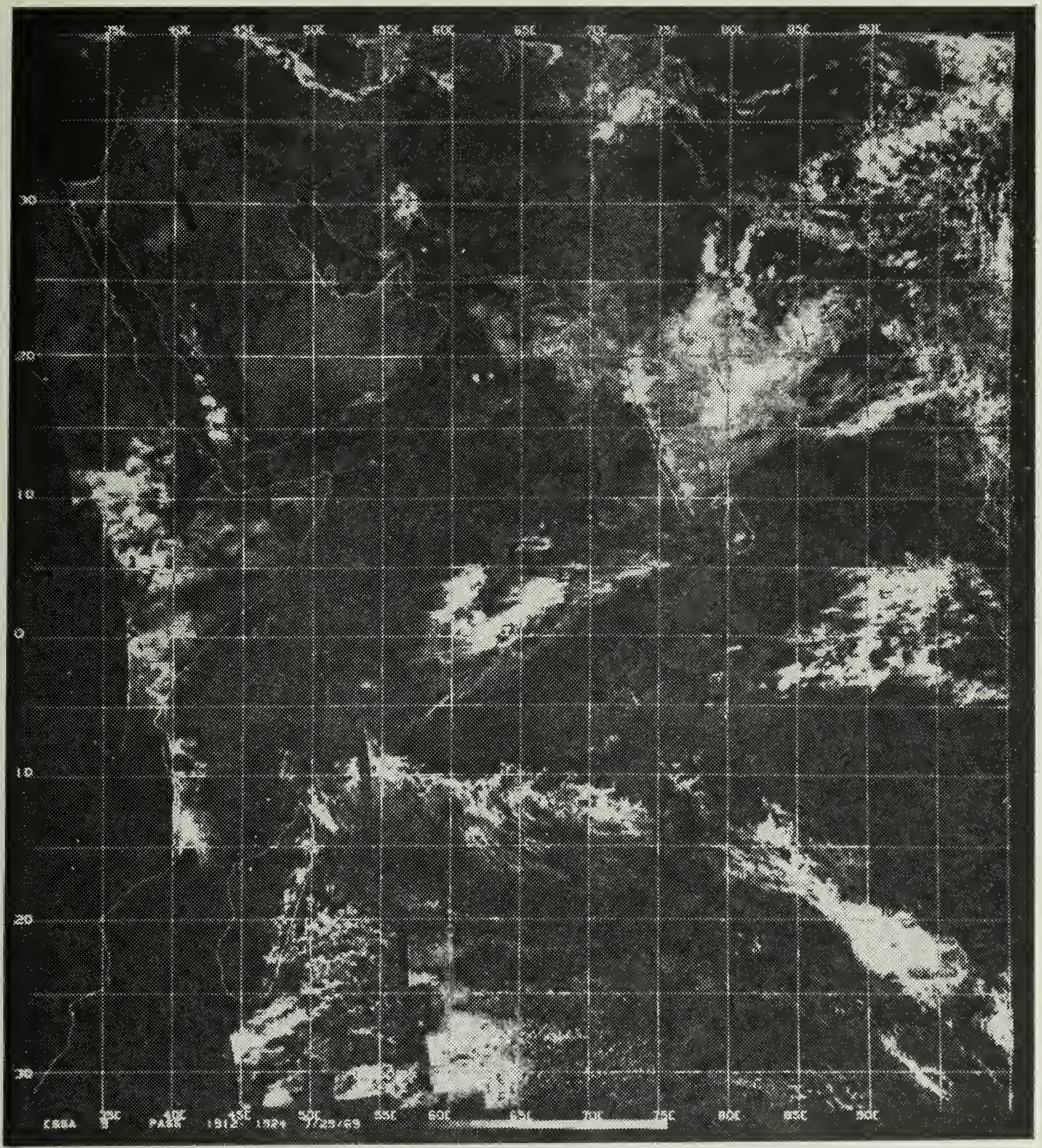


Figure C-4

Figure C-5 (opposite)
Digitized ESSA-9 satellite photograph dated August 12, 1969

Features

This photograph shows a very intense monsoon depression located at the head of the Bay of Bengal. This figure should be compared with Figure C-4. The circulation associated with the depression is easier to make out but is still not obvious to the inexperienced eye. Again note that the main precipitation area is to the southwest (or south) of the system (paragraph 4.3.2). Note also the clearing over the southern part of the bay. An easily detected feature is the cumulus activity to the north of the center. This is noticeably more intense than that seen in Figure C-4 and is a good indicator of the existence of an intense monsoon depression (Srinivason et al, 1971). The cloudiness over the Arabian Sea is associated with a mid-tropospheric cyclone.

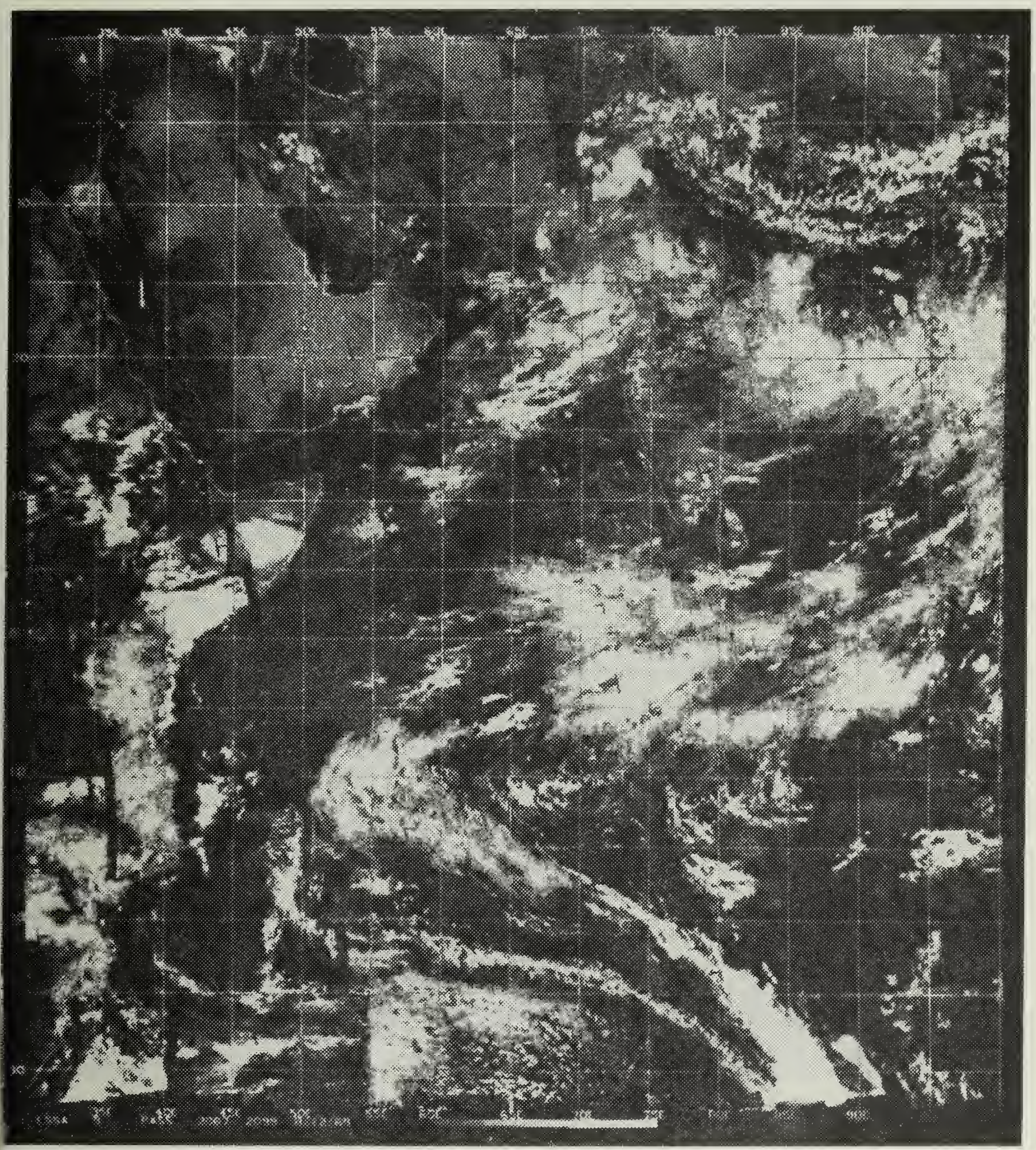


Figure C-5

Figure C-6 (opposite)
<u>Digitized ESSA-9 satellite photograph dated July 19, 1969</u>

<u>Features</u>

This photograph has been selected to show a typical intense southwest monsoon flow. There is no monsoon depression present but, comparing this figure with Figure C-4 and C-5, it will be appreciated how difficult it is to detect such a feature solely from a satellite photograph; see paragraph 4.3.3. Of particular note is the clearing along the foothills of the Himalayas associated with the monsoon heat trough (paragraph 4.2); this can also be seen in Figures C-4 and C-5.

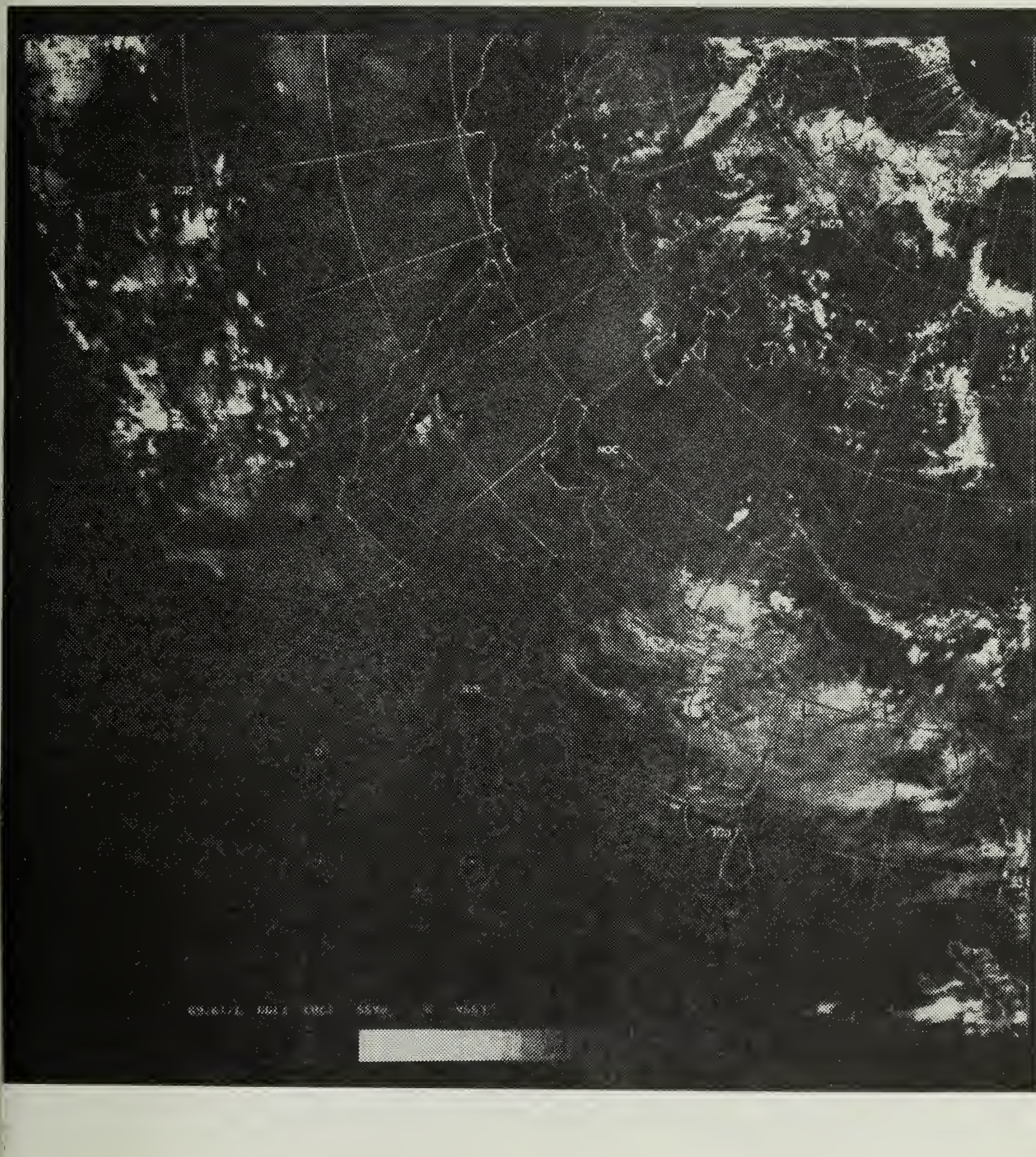


Figure C-6

Figure C-7 (opposite)
Digitized ITOS-1 satellite photograph dated October 14, 1970

Features

This picture was taken during the fall transition season and an active convergence zone is evident over the southern part of the Bay of Bengal. Recall that the lines of cloud do not necessarily correspond to the pressure trough (paragraph 4.2.3). Major cloud masses should be closely monitored for development of circulation. It is at this time of the year that heavy rainfall occurs over southern India and Ceylon, while cloudiness decreases in the northern part of the bay (paragraph 6.2.4). However, scattered but locally intense convective activity can be seen over the central bay.

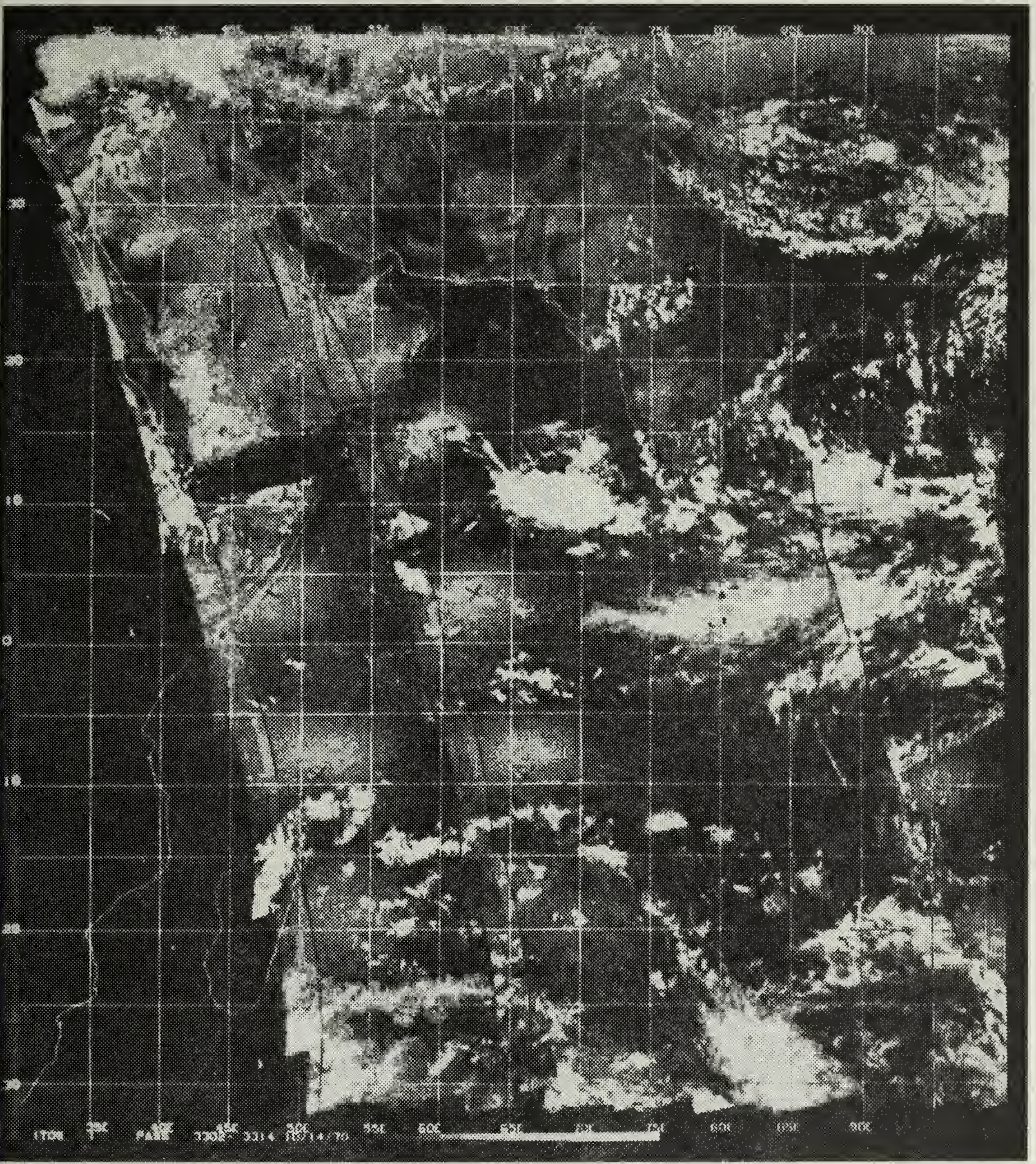


Figure C-7

Figure C-8 (opposite)

Digitized ITOS-1 satellite photograph dated November 6, 1970

Features

This shows an intense circulation developing over the Bay of Bengal. Figure C-9 shows the same circulation 3 days later.

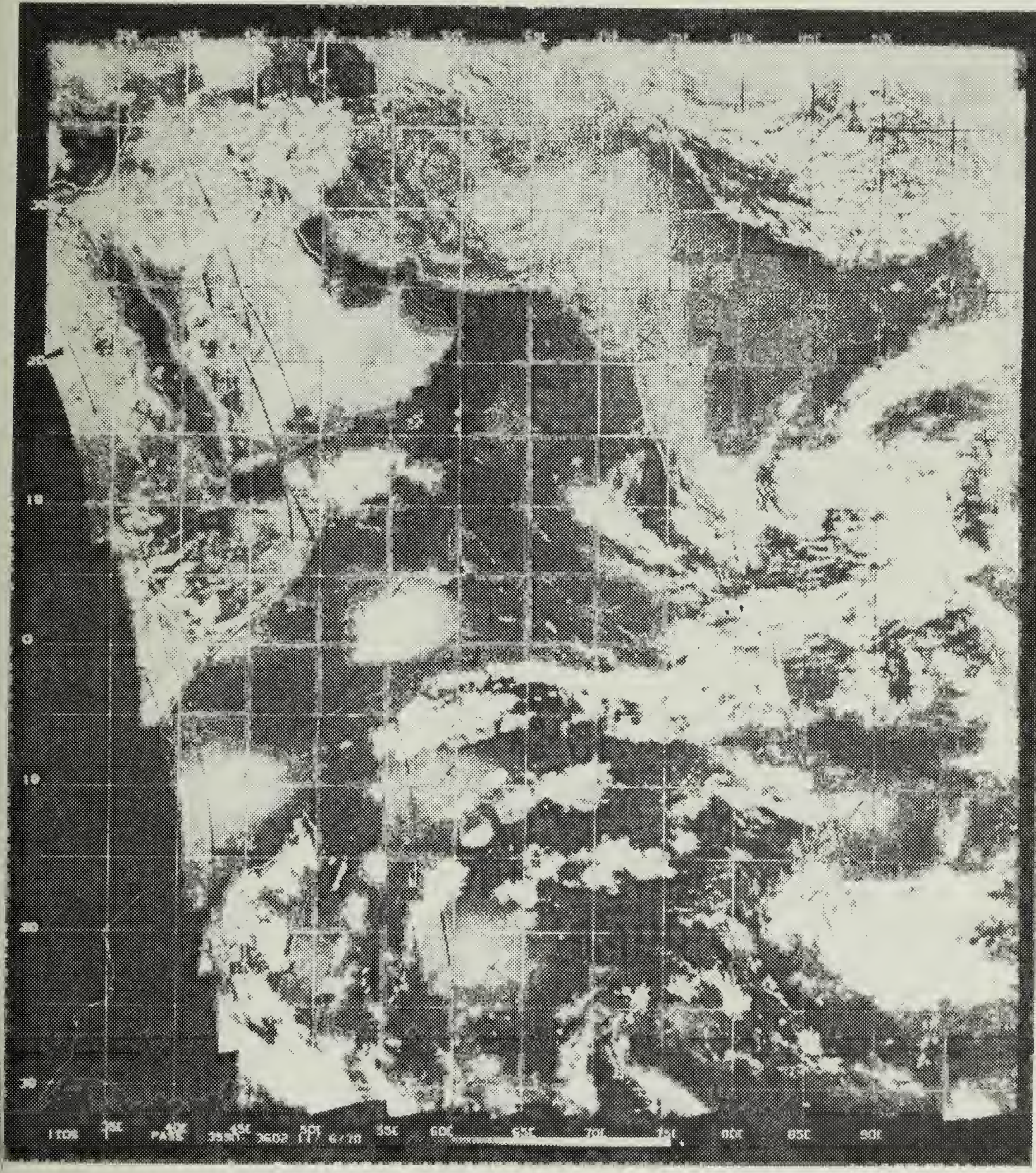


Figure C-8

Figure C-9 (opposite)

Digitized ITOS-1 satellite photograph dated November 9, 1970

Features

This shows the same storm as that in Figure C-8 but 3 days later. Intense outflow is evident toward the northeast. From these two photographs it can be seen that a ship initially located at the head of the Bay of Bengal would have been presented with an interesting problem in evasion. This storm developed hurricane force winds and caused unprecedented loss of life in the low-lying land at the head of the bay.

Figure C-9

Figure C-10 (opposite)
Digitized ESSA-9 satellite photograph dated December 8, 1969

Features

There are two primary features of interest. Near 30N, 65E there is a cloud mass associated with a western disturbance of the "overcast mass" type (paragraph 4.7). This formed near the Persian Gulf and moved northeast. The cloud mass affecting the Indian Peninsula is associated with the remains of a tropical storm which reached the coast one day before the photograph. Note the showers/squalls remaining over the Bay of Bengal.

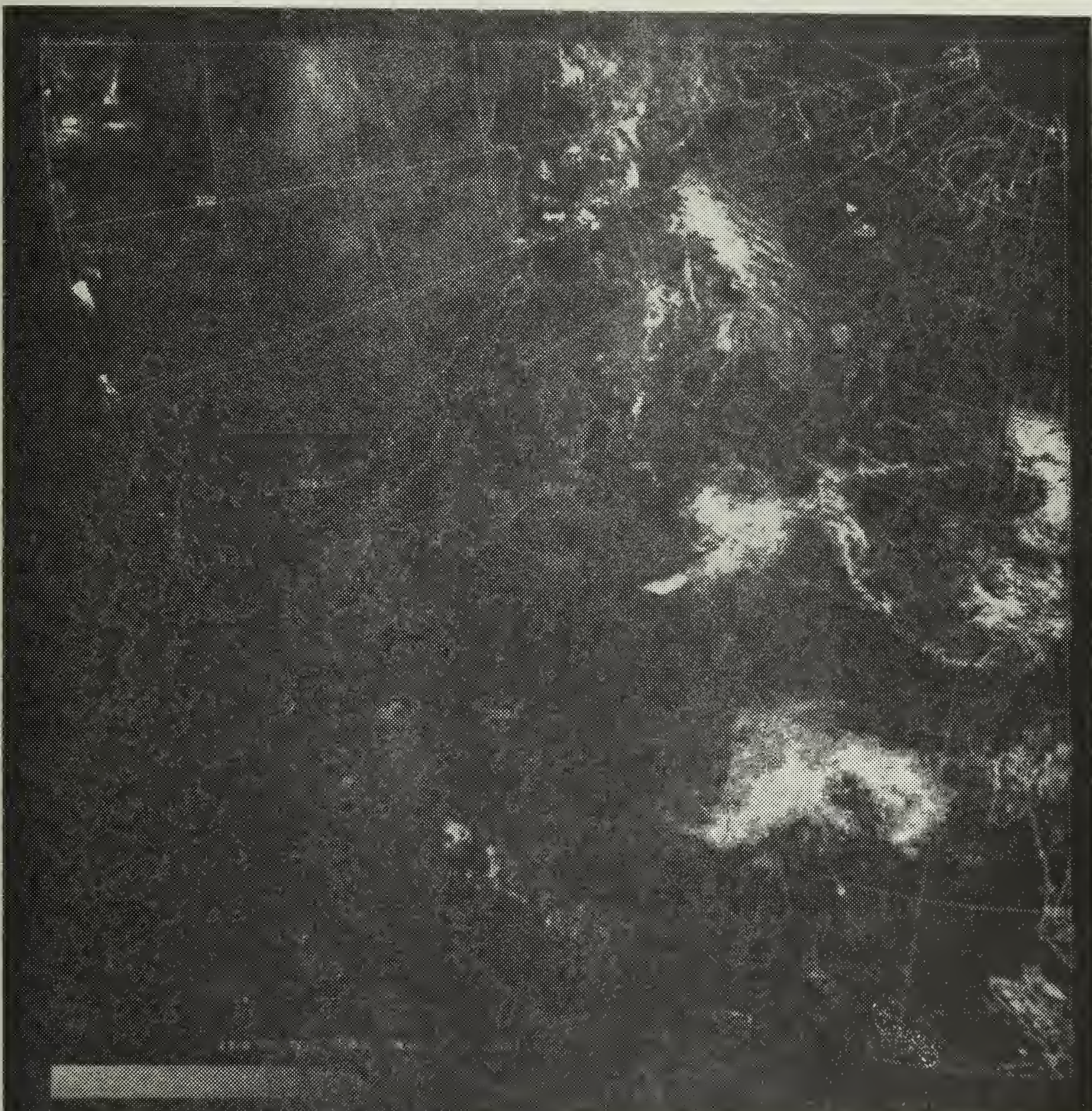


Figure C-10

APPENDIX D

ABBREVIATED TABLE OF BEAUFORT WIND SCALE

Beaufort Force	Speed (Knots)	Terminology	Tropical Cyclone Definition Used by the India Meteorological Department
0	0		
1	1 - 3		
2	4 - 6		
3	7 - 10		
4	11 - 16		
5	17 - 21		
6	22 - 27	Strong winds	
7	28 - 33		Tropical depression (winds $\leq$ 33kt)
8	34 - 40	Gale force winds	Moderate cyclonic storm
9	41 - 47		
10	48 - 55	Storm force winds	Severe cyclonic storm
11	56 - 63		
$\leq$12	$\leq$ 64	Hurricane force winds	Severe cyclonic storm with a core of hurricane winds